NASA TM-80123



# NASA Technical Memorandum 80123

NASA-TM-80123 19790023988

# REVIEW OF DESIGN AND OPERATIONAL CHARACTERISTICS OF THE 0.3-METER TRANSONIC CRYOGENIC TUNNEL

Edward J. Ray, Charles L. Ladson, Jerry B. Adcock,
Pierce L. Lawing, and Robert M. Hall

SEPTEMBER 1979



National Aeronautics and
Space Administration

**Langley Research Center**
Hampton, Virginia 23665

# REVIEW OF DESIGN AND OPERATIONAL CHARACTERISTICS OF THE 0.3-METER TRANSONIC CRYOGENIC TUNNEL*

Edward J. Ray, Charles L. Ladson, Jerry B. Adcock,
Pierce L. Lawing, and Robert M. Hall
NASA Langley Research Center
Hampton, Virginia 23665

## SUMMARY

The past six years of operation with the NASA Langley 0.3-m Transonic Cryogenic Tunnel (TCT) have shown that there are no insurmountable problems associated with cryogenic testing with gaseous nitrogen at transonic Mach numbers. The fundamentals of the concept have been validated both analytically and experimentally and the 0.3-m TCT, with its unique Reynolds number capability, has been used for a wide variety of aerodynamic tests. Techniques regarding real-gas effects have been developed and cryogenic tunnel conditions can be set and maintained accurately. It has been shown that cryogenic cooling by injecting liquid nitrogen directly into the tunnel circuit imposes no problems with temperature distribution or dynamic response characteristics. Experience with the 0.3-m TCT has, however, indicated that there is a significant learning process associated with cryogenic, high Reynolds number testing. Many of the questions have already been answered; however, factors such as tunnel control, run logic, economics, instrumentation, and model technology present many new and challenging problems.

*Paper presented at the First International Symposium on Cryogenic Wind Tunnels, The University, Southampton, England, April 3-5, 1979.

## SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| AOA | angle-of-attack |
| BL | boundary layer |
| $c$ | chord |
| $C_{A_B}$ | axial force coefficient resulting from base drag |
| $C_D$ | drag coefficient |
| $C_{D,\beta}$ | drag coefficient due to boattail drag |
| $\Sigma\Delta C_{D,\beta}$ | summation of incremental values of $\Delta C_{D,\beta}$ |
| $C_m$ | sectional pitching moment coefficient |
| $C_n$ | sectional normal force coefficient |
| $C_p$ | pressure coefficient |
| DAS | data acquisition system |
| hp | horsepower |
| $L$ | length from nose to beginning of boattail |
| $M$ | Mach number |
| $p_t$ | stagnation pressure |
| $\Delta p_t$ | loss in total pressure |
| $q$ | dynamic pressure |
| $R_c$ | Reynolds number based on chord |
| $R_L$ | Reynolds number based on vehicle length |
| $t$ | time |
| $T_t$ | total temperature |

| | |
|---|---|
| $T_{t,amb}$ | ambient total temperature |
| $\bar{T}_t$ | area averaged total temperature |
| $\Delta T$ | stream temperature minus wall temperature |
| $U$ | mean streamwise velocity |
| $u'$ | fluctuating velocity |
| $v$ | local velocity |
| $V$ | free-stream velocity |
| $x$ | local station |
| $\alpha$ | angle-of-attack |
| $\gamma$ | specific heat ratio |
| $\sigma$ | standard deviation |

## INTRODUCTION

Personnel at the NASA Langley Research Center have been investigating the application of the cryogenic concept to high Reynolds number transonic tunnels since the autumn of 1971. The initial efforts were aimed at extending the theoretical analysis and modifying a small low-speed model tunnel for cryogenic operation.[1] The encouraging results obtained from these initial studies stimulated the design and construction of the Langley Pilot Transonic Cryogenic Tunnel. The initial proof-of-concept results obtained in the pilot tunnel[2,3,4] had a profound effect on the U.S. decision to apply the cryogenic concept to the National Transonic Facility (NTF). As a result of the successful operation during these validation studies, the pilot tunnel was later reclassified as the 0.3-

meter transonic cryogenic tunnel (TCT). The purpose of this paper is to: (1) review the development, design characteristics, and current capabilities of the 0.3-m TCT, (2) present highlights of cryogenic operational experience, and (3) indicate future plans for the 0.3-m TCT facility.

This paper is presented from the standpoint of a wind tunnel user and represents a broad overview based on six years of cryogenic wind tunnel experience. Details of many of the analytical and experimental studies discussed herein are subjects of complete papers which are referenced herein as appropriate.

## HISTORICAL DEVELOPMENT, CHARACTERISTICS, AND CAPABILITIES OF THE 0.3-m TCT

Pilot tunnel concept.- The 0.3-m transonic cryogenic tunnel was placed in operation at NASA's Langley Research Center in the autumn of 1973. During that time there was an urgent requirement to select a valid and economically feasible approach for a national high Reynolds number transonic tunnel. As a result of this urgency, the 0.3-m TCT was designed, constructed, and calibrated in an impressively short period of about eight months. At that time, the 0.3-m TCT was envisioned as a "short-life" (about 60 operating hours), pilot tunnel, with the primary purpose of validating the fan-driven cryogenic concept at subsonic and transonic Mach numbers. The pilot tunnel was a continuous flow, fan-driven tunnel with a slotted octagonal test section, 34.3 cm across the flats. A photograph of the tunnel is shown in figure 1. From the vantage point shown in figure 1, the fan is in the lower left hand corner of the tunnel circuit and the flow is counter-clockwise.

The tunnel was constructed of 6061-T6 aluminum alloy and was originally encased in thermal insulation consisting of about 12.7 cm of urethane foam, covered with a fiberglass-reinforced epoxy vapor barrier (see figure 2). The fan is driven by a 2.2 MW (3000-hp) variable-frequency motor. With the three-dimensional octagonal test section installed, the Mach number of the pilot tunnel could be varied from about 0.05 to 1.2 at stagnation pressures varying from about 1.2 to 5 atmospheres. Liquid nitrogen was originally stored in 15,000 liter mobile trailers. The tunnel temperatures could be reduced to about 78 K by spraying liquid nitrogen directly into the tunnel circuit. Viewing ports 3.5 cm in diameter were provided for monitoring the test section and nitrogen injection zones.

Reclassification to operational facility.- In retrospect, the operation of the pilot tunnel as the first transonic cryogenic tunnel was very successful and relatively trouble-free. As a result of the successful operation during the validation studies, the pilot tunnel was reclassified by NASA (with Congressional approval) as the 0.3-m transonic cryogenic Tunnel. Shortly after the reclassification, an engineering team representing a variety of disciplines (electrical, structural, cryogenic, aerodynamic, and safety) was formed to inspect the 0.3-m TCT and evaluate its long range suitability as a research facility from the standpoint of design features and structural integrity. Considering the haste of the original construction and installation and the 18 months of intensive cryogenic operation, there were surprisingly few major deficiencies. There was, however, one general class of internal structural damage which occurred in cases where "spoke-like" aluminum struts were rigidly attached to the tunnel pressure vessel and to central "hub-like" structures (see figure 3). This class of failures was later eliminated with a redesign which provided for polytetrafluroethylene cushioned "T" slots at the central hub attachment points (see figure 4).

Installation of the two-dimensional insert.- The original three-dimensional test section was replaced with a 2-D test section insert during the summer of 1976, taking advantage of the interchangeable test section feature of the 0.3-m TCT (see figure 5). The two-fold purpose of this extensive modification was to assess the feasibility of two-dimensional testing at cryogenic temperatures and to take additional advantage of the very attractive high unit Reynolds number capability of the relatively small, economical test facility. The two-dimensional insert consisted of a new contraction section, a rectangular pressure plenum encompassing a 20 x 60 cm test section and a completely new diffuser. A photograph of the original two dimensional test section installed in the 0.3-m TCT is shown in figure 6. The photograph indicates only one nitrogen injection station located in the diffuser section of the "upper-leg". This location reflects the results of some injection studies which indicated that adequate cooling and mixing could be accomplished with the upper injection station alone and an original lower injection station was eliminated.

As shown in figure 7, the two-dimensional test section provides removable model modules. In this photograph, the plenum lid and test-section ceiling have been removed and the module is in the raised position. This removable feature and duplicate module assemblies allow for the complete preparation of one model during the testing of another model. The cryogenic tunnel incorporates computer-driven angle-of-attack and momentum rake systems. The momentum rake shown in figure 8 is programmed to traverse automatically through the wake, determine the boundaries of the wake, and then step through the wake at a prescribed rate and number of steps. The two-dimensional test section has provisions for treatment of the sidewall boundary layer. This is accomplished by "removal" of the boundary layer through porous sidewall inserts (shown in figure 8) located just upstream of the model station.

<u>Recertification to 6 atmosphere capability</u>.- During most of 1978, an extensive program was undertaken to recertify the entire tunnel circuit for testing at 6 atmospheres stagnation pressure. This upgrading was supposedly consistent with the strength of the basic shell and would provide an additional Reynolds number capability and the ability to approximate more

closely the stagnation pressures to be used in the National Transonic Facility. The tunnel was completely stripped of its original insulation, and the entire circuit visually inspected and x-rayed for any possible structural damage. (It is estimated that at this time, the tunnel had operated for about 2000 hours and had been subjected to about 600 complete pressure-temperature cycles.) In order to comply with USA codes and requirements for testing and certification of the 6 atmosphere pressure vessel, a considerable number of the original welds were replaced with higher quality welds and certified by x-rays and other forms of non-destructive testing. In addition, a major portion of the contraction section was completely replaced. Several other sections were reinforced with additional structural members. It should be noted, however, that even after 4 years of fairly intensive cryogenic operation at pressures up to 5 atmospheres, the pressure vessel maintained structural integrity. On completion of the structural modification, the entire circuit was pressure tested to 1.5 times the 6 atmospheres operating pressure.

During the recertification period, the original insulation was replaced with a relatively simple and inexpensive insulation concept which facilitates rapid, uncomplicated modifications and repairs. The primary insulation material is chopped untreated fiberglass loosely sewn into a mat approximately 2.5 cm (1.0 inch) thick. A photograph showing the application of the new insulation material to a portion of the tunnel is shown in figure 9. Four thicknesses of material are wrapped around the tunnel and bound with an outer layer of fiberglass cloth. Moisture control is accomplished by the outer layer, a fiberglass/elastomeric coating, and an internal gaseous nitrogen purge system supplied by ullage gas from the $LN_2$ storage tanks. A pressure controller maintains a small positive pressure inside the insulation system. During application, the four mats of insulation are compressed to a final thickness of about 7.6 cm, providing a reasonably efficient insulator with a steady state heat leak of about .0063 watts/cm$^2$ at the maximum temperature difference across the tunnel wall/insulation layer. Initial tests performed with the new insulation indicated that it performs satisfactorily and fully meets the design requirements of simplicity and low cost.

Current capabilities.- The 0.3-m TCT with the two-dimensional test section installed is capable of operating at temperatures varying from about 78 K to about 327 K and stagnation pressures ranging from slightly greater than 1 to 6.0 atmospheres. Mach number can be varied from about 0.05 to 0.95. The ability to operate at cryogenic temperatures combined with the newly acquired 6 atmosphere pressure capability provides an extremely high Reynolds number capability at relatively low model loadings. For example, to achieve an equivalent Reynolds number in an ambient-temperature pressure tunnel of the same size would require a stagnation pressure capability of about 36 atmospheres. In addition, the unique ability to vary pressure and temperature independently of Mach number provides independent control and assessment of aeroelastic, viscous, and compressibility effects on the aerodynamic parameters being measured.

Several examples of this attractive capability are shown in figure 10. This figure shows dynamic pressure-Reynolds number envelopes for a 15.24 cm chord two-dimensional model at Mach numbers of 0.20, 0.60, and 0.87. The conditions which define the outer boundaries of these envelopes are the horizontal lines of maximum and minimum pressure and the diagonal lines of maximum and minimum temperature. Conventional pressure tunnels can operate only along or very near to the ambient temperature lines, and increases in Reynolds number can only be accomplished by increasing the stagnation pressure. This obviously results in large increases in dynamic pressure, q, and consequent increases in model loading and distortion. The addition of temperature as an independent variable expands the envelope, and studies at constant dynamic pressure or at constant Reynolds number can be accomplished with just one model. For example, at a Mach number of 0.87 and a stagnation pressure of 6 atmospheres, a pure Reynolds number study can be made with Reynolds number varying from about 10 to 60 million.

Figure 11 represents a summary of the two-dimensional 0.3-m TCT Mach number and Reynolds number test capability, and the flight Reynolds number design conditions for two classes of aircraft. The general aviation design envelope, shown in the low Mach number, low Reynolds number corner of the figure, has not changed significantly over the past several decades. The transport-cargo aircraft design trend, however, has changed rapidly and dramatically. The large transport-cargo types, such as the 747 and C-5, tend to establish the upper requirement for two-dimensional design considerations. It can be noted from figure 11, that the 0.3-m TCT provides an adequate Mach number and Reynolds number capability to simulate the design flight condition for the largest class of current day, transport-cargo aircraft.

## EXPERIMENTAL VALIDATIONS, CRYOGENIC TECHNIQUES, AND OPERATING EXPERIENCE

Original proof-of-concept tests.- The initial theoretical real-gas studies made at the Langley Research Center indicated that for moderate operating pressures, flow characteristics are insignificantly affected by real-gas imperfections of nitrogen at cryogenic temperatures. However, due to the fact that the cryogenic concept represented an entirely new type of wind tunnel testing, the first noncalibration test was designed to provide experimental confirmation of the cryogenic concept. The configuration selected for these studies was a 12-percent thick, NACA 0012-64 airfoil equipped with pressure orifices. A photograph of the model installed in the three-dimensional test section is shown in figure 12. The 13.7 cm chord airfoil completely spanned the octagonal test section. The insert sketch included in figure 12 indicates that at subcritical speeds, this airfoil has a "flat-top" velocity distribution, similar to the upper surface distribution of current supercritical designs. This feature added to the appeal of the selection of this airfoil for the proof-of-concept tests.

There are several conditions which were selected to assure a fair and adequate cryogenic evaluation: (1) tests at ambient and cryogenic temperatures were to be made in the same tunnel, on the same model, at identical Mach numbers and Reynolds numbers; (2) the airfoil was to be tested with free transition to allow any possible temperature effect on boundary-layer development; (3) the symmetrical airfoil was to be tested at a lift coefficient of zero to eliminate any shape or angle-of-attack change due to dynamic-pressure differences; and (4) the test Mach number would exceed the leading edge Mach number of typical sonic transport designs. The test results obtained in this important proof-of-concept study indicated excellent agreements between the selected ambient and cryogenic cases at both subcritical and supercritical conditions[4].

Additional experimental tests were made in support of the analytical real-gas analysis[5] and to determine the proper procedures for setting the tunnel test conditions. For these tests, the tunnel Mach number was set according to the pressure ratio ($p/p_t$) as indicated by the real-gas isentropic expansion solution for nitrogen or by the ideal-gas equations in combination with the actual ratio of specific heats for the stagnation conditions under consideration.

The effect of these two procedures for setting Mach number on the two-dimensional airfoil pressure distributions were determined. Samples of the results obtained from this study are presented in figure 13 for a nominal Mach number of 0.85. A baseline pressure distribution is the high pressure, ambient temperature case (square symbols) since the thermodynamic properties for this condition ($\gamma = 1.40$) are such that use of either procedure gives the same result. For the cryogenic 1.2 atmosphere case, there is excellent agreement with the baseline distribution when the tunnel is set by the real-gas $p/p_t$ ratio (circular symbols) indicating the validity of the real-gas procedure. When the tunnel was set by the ideal-gas equation and the actual ratio of specific heats, 1.44 (dashed curve), the shock location occurred some 2 or 3 percent further downstream on the chord of the airfoil. Even for this case, where the specific heat ratio is very close to the ideal diatomic value of 1.4, it is obvious that this procedure for setting Mach number is incorrect. These results support the findings of the analytical work where it was shown that the use of ideal-gas equations in combination with actual specific heat ratios at cryogenic conditions results in erroneous indications of the magnitude of real-gas effects. When this procedure for setting Mach number was applied at a high pressure, low temperature condition (see long-short dashed curves, figure 13) where the specific heat ratio is 1.52, the recompression shock is located about 10 percent further downstream on the airfoil. (It is realized that this case represents a considerably higher Reynolds number, but the detailed studies of the 0012-64 airfoil had shown that the shock location for this particular airfoil was extremely insensitive to variations in Reynolds number within the range of these studies.)

Typical operating techniques--tunnel temperature distributions.- In the 0.3-m TCT the heat of compression added to the stream by the fan is removed by spraying liquid nitrogen directly into the tunnel circuit. The liquid nitrogen is currently supplied from two vacuum insulated tanks having a capacity of about 212,000 liters (see figure 14). The flow of $LN_2$ into the tunnel circuit is regulated through four 10-bit, 11-element digital valves which are operated in accordance with command signals from a microcomputer-controller. The maximum injection rate of the liquid nitrogen pump is about 500 liters per minute with a delivery pressure of about 9.3 atmospheres. Tunnel total pressure is adjusted by means of one 8-bit digital and two conventional analog control valves in exhaust pipes leading to the atmosphere from the big end of the tunnel. Digital valves have been incorporated in the liquid and exhaust systems due to their precise and rapid control over large ranges of required flow rates.

A severe fogging problem existed with the original exhaust stack design during periods of high humidity and low wind speeds. A very simple and effective solution to this problem has been the incorporation of exhaust driven ejectors. The low pressure ejector induces ambient air at the base of the exhaust stack, which dilutes and rapidly warms the cold nitrogen gas. The resulting foggy mixture is propelled high into the air and normally dissipates rapidly and completely. (See figure 15.) A detailed description of the liquid nitrogen and exhaust systems of the 0.3-m TCT is contained in reference 6.

A record of stream and tunnel wall temperature as a function of time is shown in figure 16 to illustrate the various phases of tunnel operation during a typical run. This particular run does not include the normal pre-run purge described in reference 6 due to the fact that the tunnel had not been opened to the atmosphere prior to this test. The tunnel is normally cooled down at a rate of about 10 K/minute or less to avoid excessive thermal stresses in the tunnel structure. This particular cool-down is fairly typical and took about 40 minutes. It will be noticed that near the end of the cool-down, the cooling rate was reduced to enable the tunnel wall and stream temperatures to equalize. Figure 17 shows the temperature difference between the wall and stream for this run. It will be noted that at one point during the cool-down there was about an 80 K "lag" between the wall and stream. During the 52 minute test time, however, the differences between the wall and stream temperatures were maintained within 10 K. The normal run procedure has been to keep the wall and stream temperatures at about the same temperatures. It should be noted however, that to date there has been no evidence of any aerodynamic discrepencies due to differences in temperature between the wall and stream. In the example shown in figure 16, there were eight different test conditions established which ranged in temperatures from 86 K to 103 K at pressures between 4.3 and 5 atmospheres and Mach numbers ranging from 0.740 to 0.755. If a tunnel entry is required, the normal procedure is to warm the tunnel to ambient temperatures at a rate roughly equivalent to the cool-down rate. It has recently been proven in the 0.3-m TCT that the tunnel can be left cold when not running without any possible material damage even to the drive system. If a tunnel entry is not required, this procedure avoids the significant time and expense of warm-up and cool-down.

As mentioned earlier, the wide range of operating temperatures is obtained by spraying liquid nitrogen directly into the tunnel circuit to cool the structure and to remove the heat added to the stream by the drive fan. Because of this method of cooling, the uniformity of the temperature distribution was one of the primary areas of concern at the beginning of the 0.3-m TCT studies. In order to determine the extent of the mixing process and to evaluate the temperature distributions in the circuit, a temperature survey rig was placed just upstream of the turbulence damping screens in the low velocity area of the tunnel. A photograph of the survey rig is shown in figure 18. The rig incorporates 24 thermocouples which are evenly spaced along 8 spokes, $45^{\circ}$ apart. A sketch of the temperature survey rig showing the general location of the thermocouple probes is shown in figure 19 along with a listing of some early results which were obtained at a Mach number of 0.85. The mean value of temperature $\bar{T}_t$, the difference in the extremes in temperature, RANGE, and the standard deviation are listed for stagnation pressures from 1.20 to 5.00 atmospheres. It can be readily seen that there is a relatively uniform temperature distribution even at the extremely low cryogenic temperatures approaching free-stream saturation conditions. Since the temperature survey station is located upstream of the turbulence damping screens and the contraction section, it was expected that a more uniform distribution would occur in the test section. Subsequent temperature measurements obtained in the test section verified this assumption, and indicated that at Mach number of 0.85 at 5 atmospheres stagnation pressure and a cryogenic temperature of about 120 K, the standard deviation was about 0.2 K. In addition, preliminary tests have been made to assess the thickness of the thermal boundary layer near the tunnel walls. This preliminary assessment indicated that the thermal boundary layer is extremely thin, and that temperatures, even in the low velocity screen section of the tunnel, approach free-stream values at about 1.3 cm from the wall.

The temperature studies have shown remarkably good distributions. This is particularly encouraging in view of the fact that it is not uncommon for some classes of ambient temperature wind tunnels to have temperature gradients of over 11 K across the test section.

Validations of power requirements.-Economy in power consumption is to be expected with cryogenic operation based simply on the ideal-gas Power $\propto \sqrt{T}$. (There is also an additional decrease in power required due to the increased Reynolds number as noted in reference 7.) Figure 20 is a map of the fan power as a function of Reynolds number for a range of pressures and temperatures at a constant Mach number of 0.85. The region of the map labeled "experimentally verified" indicates the extent of current power validations. The "new capability" region is the result of the recent recertification to 6 atmospheres operating pressure. The savings in power by operating at cryogenic temperatures may be illustrated on this map by considering the example of a constant

Reynolds number of 12.5 million. The power required to produce the same Reynolds number by increasing stagnation pressure is an order of magnitude higher than the power required at the minimum cryogenic test condition. At the present time, drive system dynamics limit the fan speed and prevent operation at 300 K for Mach numbers in excess of about 0.7, therefore, at M = 0.85, as shown in figure 20, data has not been obtained at temperatures over 200 K. At a constant stagnation pressure of 3 atmospheres, testing at ambient temperatures rather than at cryogenic temperatures doubles the power requirements and reduces the Reynolds number by a factor of about 4.8. This experimental evidence substantiates that when moving from warm to cold temperatures at 3 atmospheres, the power required is about 16 percent less than that expected from the simple ideal-gas relation Power $\propto \sqrt{T}$ as a result of the sizeable Reynolds number increase and real-gas effects (reference 8). It is obvious from the power envelope of figure 20, that the relatively small 2.2 MW (3000 HP) drive motor of the 0.3-m TCT provides an adequate capability for simulating many full-scale flight conditions.

Testing at minimum temperatures.-The onset of condensation may impose a minimum operating temperature limit on "useful" cryogenic wind tunnel testing. During the condensation process a small percentage of the gas molecules condense into liquid droplets and release latent heat into the surrounding gas. This heat release changes the values of static pressure on model surfaces and decreases the value of stream total pressure.

Experimental tests in the 0.3-m TCT have been made[9,10] to determine the onset conditions of condensation effects. Figure 21 illustrates the two types of experimental devices used in the condensation studies. The initial study was made with the previously described 13.7 cm chord, NACA 0012-64 airfoil mounted at $0^{\circ}$ angle-of-attack in the three-dimensional test section. A second study involved the evaluation of stagnation pressures obtained from an array of small total pressure probes mounted in the three-dimensional test section. Figure 22 presents a sample of the total temperatures, $T_t$, and tunnel stagnation pressures, $p_t$, at which condensation effects were first detected. This figure includes results attained for both the airfoil and the total pressure probes at a Mach number of 0.85. The line denoted "local saturation" corresponds to conditions which would result in saturation locally on the airfoil. (For this example, this condition would correspond to a local Mach number of 1.2.) The line "free-stream saturation" corresponds to saturated conditions in the test section for both the airfoil and total pressure probe tests. "Tunnel reservoir saturation" corresponds to the conditions at which the low velocity areas of the tunnel would become saturated.

It will be noted from this figure that there is good agreement between the "onset" conditions determined by the two types of evaluations. In addition, these results indicate that in both cases, the onset occurred not only below the local saturation boundary, but below the boundary corresponding to saturated conditions in the test section.

The condensation studies have indicated two primary conclusions. First, the onset effects are the result of heterogeneous condensation, that is, growth of liquid nitrogen droplets which remain in the stream due to incomplete evaporation of the injected liquid nitrogen used for cooling the tunnel. Secondly, significant increases in Reynolds number test capability can be achieved by testing at temperatures below local saturation conditions while remaining above the conditions corresponding to the onset of disturbing condensation effects. In the example selected, it will be noted from figure 22 that a 15 percent increase in Reynolds number capability could be achieved by testing below the local saturation boundary.

<u>Typical calibrations</u>.-The Mach number distributions for both the three-dimensional and two-dimensional test sections have been obtained over a wide range of test conditions. A typical two-dimensional test section calibration is shown in figure 23. Static pressure measurements obtained from pressure orifices located along the floor and ceiling were used in the calculations of local Mach number. In addition to the floor and ceiling measurements, this survey included the examination of a dense array of static pressure measurements in the vicinity of the model turntable (see inset sketch figure 23). The two-dimensional models are normally centered on the turntable at the longitudinal center of the test section (station x=0). The stagnation pressure used in the Mach number calculations was obtained from a pitot tube located just downstream of

the screens. (Details regarding the data reduction process for pressures measured in gaseous nitrogen are discussed in reference 11.) Test section Mach number distributions are shown for two different temperature conditions, 300 K and 105 K, at a stagnation pressure of about 4.7 atmospheres. The Mach number distributions are generally good, indicating a maximum difference in local Mach number in the vicinity of the model turntable of about 0.002. The slight fluctuations shown in this calibration probably occurred as a result of test section width inaccuracies. Since the time of this calibration, the original two-dimensional test section has been improved by the addition of new sidewalls and an improved geometry at the entrance to the diffuser. In addition, improved instrumentation has been incorporated for the measurement of tunnel conditions which provide a Mach number resolution of .001. A preliminary study indicates that these changes have improved the Mach number distributions and increased the maximum Mach number capability to about 0.95.

The calibration studies have shown that excellent Mach number distributions can be obtained at transonic speeds in a cryogenic pressure tunnel. It appears, however, that the wide range of wall boundary conditions may make it worth while to incorporate variable wall geometry.

Run techniques and $LN_2$ usage characteristics.-It is well known that high Reynolds number simulations can be achieved by several valid methods. Regardless of how the desired increase in Reynolds number is achieved, high Reynolds number testing is expensive. In a cryogenic high Reynolds number tunnel, liquid nitrogen can be considered as another form of expensive energy. Techniques and procedures, therefore, must be used to determine the sensitivity of the test model to scale effects, determine the minimum amount of high Reynolds number testing required, and determine the least expensive way to achieve the desired test condition. Experience with the 0.3-m TCT has shown that operating with new envelopes, expanded by the ability to vary temperature, requires the development of specialized testing techniques and procedures.

Figure 24 indicates a typical two-dimensional airfoil test program and a qualitative assessment of average liquid nitrogen costs for several types of research programs. In the typical airfoil program shown in figure 24(a), the upper boundary represents the Reynolds number capability at the 6 atmosphere, cryogenic temperature conditions. It will be noted from this illustration that the highest density of tests are in the low to moderate Reynolds number range. In the low Reynolds number range for this typical airfoil, several tests are scheduled to determine the effects of artificial transition. An early assessment of the effects of artificial transition may reduce the quantity of high Reynolds number tests required and, in addition, may provide guidance for fixing transition when testing in conventional low Reynolds number wind tunnels. The conventional NACA 0012 and 0012-64 airfoils tested in the 0.3-m TCT have indicated the significant scale effects occurring in the Reynolds number range up to 10 million. It will also be noted that there are several Mach number, Reynolds number "cuts" which decrease in density at the higher, more costly, Reynolds number conditions.

The three diagonal lines shown in figure 24(b) represent comparative cost rates for a low to moderate Reynolds number program (lowest rate), the typical airfoil program shown in figure 24(a), and a relatively expensive high Reynolds number program. A data point (one angle of attack at one test condition) in this illustration consists of airfoil upper and lower surface pressure distribution, and a drag coefficient obtained from the traversing momentum rake described earlier. The vertical lines represent: (1) the time required for one data point on an airfoil in the 0.3-m TCT with the existing open-loop tunnel control capability, (2) the predicted time per point with computer-based tunnel controls, and (3) the predicted time per point with computer-based controls, an improved data acquisition system, and individual pressure transducers.

It should be emphasized that the time required to acquire a data point for an airfoil is extremely long compared to other types of testing such as force testing using a strain gage balance. The cost rates shown, however, represent the relative costs of low, typical, and high Reynolds number studies. It can be seen from this illustration that the cost of a high Reynolds number data point is approximately 7 to 8 times greater than the cost of a low Reynolds number point. In addition, the best procedure for obtaining a desired test condition is dependent upon such factors as the time requirement at each condition and the overall requirements of the test program. For instance, for a low to moderate Reynolds number program in a cryogenic pressure tunnel, it is cost effective to obtain the desired conditions with pressure changes rather than large temperature changes due to the significant costs of cooling the tunnel and the gas to cryogenic temperatures. If, however, there is a requirement for remaining at selected test conditions for long periods of time, there is a crossover point at which it would be less expensive to achieve the desired conditions by reducing temperature. There are also optimum "paths" in changing from one condition to another. For instance, if a moderate to high Mach number is required at a lower temperature, it would be advisable to reduce the heat input from the drive fan to some optimum low level by reducing the Mach number while reducing the temperature, keeping in mind any limits on permissible differences in temperatures between the stream and the tunnel structure. The fundamentals of these operating procedures are straightforward, but to optimize these details it might become cost effective to incorporate a micro-processor or a tunnel control computer with the ability to "order" the test in either a least time or least cost arrangement. Figure 24(b) indicates that tunnel computer control would reduce the present time to acquire a typical airfoil data point by about 35 percent. This il-ilustration also shows that very substantial reductions in nitrogen usage and data acquisition time can be achieved by using an expanded data acquisition system and individual pressure transducers in place of the existing pressure scanning valves.

A math model of the 0.3-m TCT and a hybrid computer simulator of the tunnel have been developed by Balakrishna of Old Dominion University and Thibodeaux of the Langley Research Center with the ultimate goal of providing complete microprocessor-computer control for the 0.3-m TCT.

Dynamic response--tunnel simulations.-A preliminary investigation was recently made to determine the dynamic response characteristics of the 0.3-m TCT. A sample of these results is shown in figure 25. Three command impulses (shown on the lower portion of the figure) were made to the tunnel. These inputs were achieved by first pulsing the 6.25 percent element of the digital gaseous exhaust valve, followed by pulsing of the 6.25 percent element of the digital liquid nitrogen injection valve, and lastly, a 100 rpm "pulse" in the drive motor speed. It will be noted from the Mach number, stagnation pressure, and stagnation temperature responses that the process is stable and well-behaved with good mixing characteristics. There is no evidence of unstable thermal conditions, pronounced acoustical modes, or other frequency dependent traits.

These experimental results are being used to improve the existing math model by reconciling the tunnel and simulator responses. The temperature and pressure control loops have been closed on the simulator and micro-processors are being designed to incorporate the control laws for the 0.3-m TCT. The tunnel response and optimal control studies are continuing and it is expected that the Mach number loop will be closed in the near future.

## MODEL TESTING EXPERIENCE--FULL SCALE SIMULATIONS

The operational experience in the 0.3-m TCT has included a broad variety of models and range of instrumentation. The scope has probably been as extensive as would normally be experienced in conventional wind tunnel testing. During several of these studies, the 0.3-m TCT, with its unique operating envelopes and high Reynolds number capability, enabled the simulation of full-scale conditions.

Strain gage balance model tests.-The initial strain gage balance tests in the 0.3-m TCT were made in the three-dimensional test section. Photographs of the strain gage model mounted in the test section and of the model and balance are shown in figure 26. The three-dimensional model installed on the experimental balance was a thick highly swept delta wing with sharp leading edges. The purposes of these tests were to (1) investigate any possible effects of cryogenic conditions on a flow phenomenon characterized by a leading-edge vortex separation and reattachment, and (2) to obtain cryogenic experience with an electrically heated strain gage balance. There were some problems associated with balance zero shifts but the moment and force results[11] indicate that flows with leading-edge vortex effects are duplicated properly at cryogenic temperatures.

Base-drag studies.- One of the advantages of the cryogenic tunnel concept is, of course, the capability of covering a large Reynolds number range while maintaining the tunnel dynamic pressure at a constant level. This capability eliminates the variations in aeroelastic effect that occur when tunnel stagnation pressure is used to generate the desired Reynolds number variation. An early exploitation of this advantage was the measurement of the base drag of the space shuttle orbiter in the three-dimensional test section of the 0.3-m TCT. In order to eliminate the sting interference effect on the base, the model was supported by slender wing tip extensions which, in a conventional pressure tunnel, might have been subjected to sizeable and varying torsion effects. A photograph of the 0.0045-scale model installed in the test section is shown in figure 27. Figure 28 shows some selected results obtained during this study. Thirteen static pressures were measured at the base of the model (see inset sketch) with individual pressure transducers. Figure 28 shows the base axial force coefficients determined at Mach numbers of 0.8 and 0.6 during various tests in other wind tunnels using sting mounted models (open symbols) and the data obtained on the wing-tip mounted model in the 0.3-m TCT (solid, circular symbols). The solid lines are the empirical estimates made by the contractor for interference-free conditions for the orbiter base axial force coefficients. As can be seen, there is excellent agreement between the previously estimated base characteristics and the cryogenic tunnel results. The results of previous tests of sting-mounted models in other wind tunnels gave values substantially below the estimates and the 0.3-m TCT test results. These differences are presumed to be associated with sting interference effects.

Boattail drag studies.-The high Reynolds number testing experience in the 0.3-m TCT has shown that Reynolds number effects can sometimes be completely hidden by extraneous effects such as inaccurate tunnel conditions, sting interference, inadequate instrumentation, or relatively minor model inaccuracies. As an example, the 0012-64 airfoil studies indicated the extreme sensitivity of the pressure distribution of that class of airfoil to Mach number. During these high Reynolds number tests, it was observed that changes in Mach number as small as .003 resulted in a shift in shock position larger than that produced by changes in Reynolds number. In addition, the detection of gross Reynolds number effects can be extremely elusive and difficult due to compensating localized Reynolds number effects. An illustration of this type of aerodynamic behavior was observed during the study of several boattail configurations.

Boattail drag studies were undertaken in the 0.3-m TCT due to concern over the effect of Reynolds number variation on boattail pressure drag. A photograph of one of the boattail models mounted in the three-dimensional test section of the 0.3-m TCT is shown in figure 29. Investigations at the NASA Lewis Research Center had identified possible large effects of Reynolds number variations on installed boattail drag. At the Lewis Center, flight tests were made using an F-106B aircraft with two research nacelles mounted under the wings. (See insert photograph, figure 30.) The boattails were mounted on the nacelles and the aircraft was flown over a range of altitudes to obtain drag data over a large Reynolds number range. In addition to these flight tests, wind tunnel tests were made on two subscale models of the flight test configuration. The range of the Lewis flight tests and wind tunnel tests are shown in figure 30. The results from these tests, as shown in figure 30, indicated extremely large Reynolds number effects on boattail drag, showing that the low Reynolds number wind tunnel data could not be extrapolated to flight conditions.

The 0.3-m TCT studies[13-17] were initiated to determine the effects of Reynolds number on boattails. The test envelope in figure 30 shows that with the 0.3-m TCT cryogenic-pressure capability the existing flight and wind-tunnel test range could be completely surveyed. The 0.3-m TCT results show essentially no change in the boattail pressure drag with Reynolds number (see figure 30). This trend essentially agrees with theoretical predictions[15] and it was concluded that the difference between the flight test results and other wind-tunnel results was caused by installation effects.

As noted earlier, the boattail configurations were found to be extremely sensitive to local scale effects. This behavior is illustrated in figure 31. As the Reynolds number is increased, static pressure coefficients in the expansion region of the boattail become more negative. However, the pressure coefficients in the recompression region of the boattails became more positive. The two behaviors were compensating, with the net result being no discernable effects of Reynolds number on boattail drag. This compensating effect is illustrated vividly by the incremental boattail pressure drag characteristics shown in figure 31.

This investigation, as with all investigations which have been made in the 0.3-m TCT, included tests designed to provide exact Reynolds number and Mach number comparisons at ambient and cryogenic temperatures. Even with the extreme sensitivity of the boattail characteristics to local scale effects, the ambient-cryogenic comparison shows excellent agreement[17].

Full-scale cooling coil study.-Gaseous nitrogen has been shown to be a valid test gas at temperatures ranging from higher than ambient to just above those resulting in the onset of condensation effects. From an economic standpoint, however, it may be desirable to include a highly efficient chilled water heat exchanger in the circuit of cryogenic wind tunnels. This would increase the versatility of a cryogenic tunnel by providing a test capability at low and moderate Reynolds numbers in air as well as in nitrogen at ambient temperatures. The Reynolds number range of a cryogenic pressure tunnel far exceeds the aerodynamic design requirements for conventional cooling coils and an improper selection could compromise the high Reynolds number efficiency of the tunnel. It is essential, therefore, in the selection of a cooling coil design, to determine the aerodynamic characteristics over the entire operating range of the tunnel.

Igoe of the Langley Research Center has made a study of various cooling coils being considered for large cryogenic-pressure tunnels. The unique features of the 0.3-m TCT provided the capability to assess the aerodynamic behavior of the cooling coils from very low to full-scale Reynolds numbers. A photograph of one of the cooling coil models installed in the two-dimensional test section is shown in figure 32. The tube bundle models completely spanned the width of the test section. The pressure drop, flow uniformity, turbulence, and noise characteristics were measured using stagnation and static pressure measurements, thermocouples, two-component hot wire probes, and microphones. Some of the instrumentation is visible in the photograph included in the figure. The hot wire probes consisted of crossed, platinum-coated 5 micron tungsten wire with an effective length-to-diameter ratio of about 250. (The hot wires were operated in the constant temperature mode.) It is obvious from this instrumentation inventory, that specialized measurements can be considered in cryogenic test environments. (On the general subject of instrumentation, a philosophy has been adopted of keeping the various transducers at ambient temperatures if at all possible in order to avoid temperature related changes in zeros and sensitivity. With but few exceptions, if the transducer must be located inside the tunnel, it is insulated and heated to ambient temperature by thermostatically controlled electric heaters. The exceptions are such things as microphones, strain-gage balances during special evaluation tests, and, obviously, hot wire probes.)

The test conditions covered during the cooling coil studies included variations in Reynolds numbers per meter from about $0.4 \times 10^6$ to $28 \times 10^6$, variation in Mach number from 0.01 to 0.10 (corresponds to the low velocity area of a large tunnel), variation in stagnation pressure from 1 to 5 atmospheres, and variation in stagnation temperature from 100K to 300K. The Reynolds number based on hydraulic tube diameter varied from about $6 \times 10^3$ to $4 \times 10^5$.

Some representative examples of the pressure loss and longitudinal turbulence data obtained on a six-row, round tube bundle and on a four-row, elliptical tube bundle are shown in figure 32. From a standpoint of cooling and hydraulic characteristics, both of these configurations would meet the necessary requirements. One fortunate aspect of this test was the fact that the 0.3-m TCT did not impose severe dynamic loading on the models. This advantage eased model construction and also proved to be advantageous from the instrumentation standpoint. For example, there was no hot wire breakage due to adverse test conditions. It is obvious from the sample results that there are significant effects of Reynolds number on the selected coil configurations. A point of interest is that at low Reynolds numbers, there is virtually no difference in the turbulence characteristics of the two coil configurations. At full scale conditions, however, the elliptical coil has the lower level of turbulence as well as significantly lower pressure loss.

Two-dimensional airfoil tests.-As previously mentioned, the two primary reasons for installing the two-dimensional insert were to evaluate the feasibility of two-dimensional testing at cryogenic temperatures and to take advantage of the high unit Reynolds number offered by a cryogenic-pressure tunnel.

Preliminary studies of a 15.24 cm, 0012 airfoil have shown that two-dimensional testing at cryogenic temperatures is feasible. A photograph of the 0012 airfoil model mounted in the test section is shown in figure 33. This photograph shows several interesting features of this cryogenic two-dimensional test section, such as the porous plates for boundary-layer removal (located just ahead of the model), the Teflon ( reference to trade names is made for identification only and does not imply endorsement by NASA ) impregnated turntables with quartz viewing-ports, the traversing momentum rake, and the insulated pressure and angle-of-attack measuring transducers. This particular angle-of-attack transducer is a direct current potentionmeter having a parallelogram linkage to the turntable. It should be noted that work is continuing on various angle-of-attack measuring schemes in an effort to increase the accuracy and reliability of the measurement of this important parameter.

A sample of the results obtained during this study are shown in figure 34. As in the case of the 0012-64, the normal force coefficient and center of pressure indicate no observable effects of Reynolds number for Reynolds numbers above about $9 \times 10^6$. It is expected that some of the more exotic airfoil designs such as supercritical or peaky may be more sensitive to scale effects than the 0012 which was selected for these tests on the basis of data from many other tunnels.

## FUTURE PLANS

Plans for the two-dimensional test section.-The study of airfoils will continue with particular emphasis on advanced designs, such as supercritical sections, thick cargo designs, peaky, and advanced fighter concepts. Two semispan turntable mounted buffet models (an unswept peaky airfoil section, and a highly swept, sharp leading-edge delta) are scheduled to be tested in the near future to evaluate the feasibility of buffet testing at cryogenic temperatures. There will be continued attempts to identify factors affecting Reynolds number sensitivity to provide guidance for the evaluation of transonic viscous flow theories and to improve the utility of conventional wind tunnels. Fundamental cryogenic research will continue with particular attention to cryogenic test techniques, tunnel control, and instrumentation.

Facility improvements and updates.-A major update is scheduled for the near future which will include the incorporation of advanced data acquisition and tunnel control computers. In addition to the primary tunnel control, the new computer capability will provide for advanced control for the sidewall boundary layer removal system. The Langley Research Center is currently working with the University of Southampton to develop a flexible wall test section for the 0.3-m TCT to eliminate blockage and stream curvature effects. In this system concept, the computer will use measured wall static pressures and aerodynamic theory to seek "free-air" streamlines and drive the test section floor and ceiling to the proper shapes with computer controlled jacks. The installation of this advanced test section would enable the testing of larger models and, as depicted in figure 35, will constitute the third phase in the overall 0.3-m TCT program. This concept, as shown in figure 36, will provide a new and expanded Reynolds number envelope which will allow simulations of full-scale flight conditions for advanced cargo designs.

REFERENCES


1. Goodyer, Michael J.; and Kilgore, Robert A.: High-Reynolds-Number Cryogenic Wind Tunnel. AIAA J., vol. 11, no. 5, May 1973, pp. 613-619.

2. Kilgore, Robert A.; Adcock, Jerry B.; and Ray, Edward J.: Flight Simulation Characteristics of the Langley High Reynolds Number Cryogenic Transonic Tunnel. AIAA Paper No. 74-80, Jan-Feb, 1974.

3. Kilgore, Robert A., Adcock, Jerry B.; and Ray, Edward J.: Simulation of Flight Test Conditions in the Langley Pilot Transonic Cryogenic Tunnel. NASA TN D-7811, 1974.

4. Ray, Edward J., Kilgore, Robert A., Adcock, Jerry B.; and Davenport, Edwin E.: Analysis of Validation Tests of the Langley Pilot Transonic Cryogenic Tunnel. NASA TN D-7828, 1975.

5. Adcock, Jerry B.: Real-Gas Effects Associated with One-Dimensional Transonic Flow of Cryogenic Nitrogen. NASA TN D-8274. Dec. 1976.

6. Kilgore, Robert A., Adcock, Jerry B., and Ray, Edward J.: The Cryogenic Wind Tunnel for High Reynolds Number Research. Paper No. 1, AGARD Fluid Dynamics Panel Symposium on Wind Tunnel Design and Testing Techniques. London, England, Oct. 1975.

7. Kilgore, Robert A.: Design Features and Operational Characteristics of the Langley 0.3-Meter Transonic Cryogenic Tunnel. NASA TN D-8304, 1976.

8. Adcock, Jerry B. and Ogburn, Marilyn E.: Power Calculations for Isentropic Compressions of Cryogenic Nitrogen. NASA TN D-8389, 1977.

9. Hall, Robert M.: Onset of Condensation Effects with a NACA 0012-64 Airfoil Tested in the Langley 0.3-Meter Transonic Cryogenic Tunnel. NASA TP-1385, 1979. (Supersedes NASA TM 78666.)

10. Hall, Robert M: Onset of Condensation Effects as Detected by Total Pressure Probes in the Langley 0.3-Meter Transonic Cryogenic Tunnel. NASA TM 80072, 1979.

11. Kilgore, Robert A. and Davenport, Edwin E.: Static Force Tests of a Sharp Leading Edge Delta-Wing Model at Ambient and Cryogenic Temperatures with a Description of the Apparatus Employed. NASA TM X-73901, 1976.

12. Adcock, Jerry B., Kilgore, Robert A., and Ray, Edward J.: Cryogenic Nitrogen as a Transonic Wind Tunnel Test Gas. AIAA Paper No. 75-143, Jan. 1975.

13. Reubush, David E.: The Effect of Reynolds Number on Boattail Drag. AIAA Paper No. 75-63, 1975. Also Journal of Aircraft, Vol. 13, no. 5, May, 1976, pp. 334-337.

14. Reubush, David E.: The Effect of Reynolds Number on the Boattail Drag of Two Wing-Body Configurations, AIAA Paper No. 75-1294, 1975. Also Reynolds Number Effects on Boattail Drag of Wing-Bodies, Journal of Aircraft, Vol. 14, No. 5, May, 1977, pp. 455-459.

15. Reubush, David E., and Putnam, Lawrence E.: An Experimental and Analytical Investigation of the Effect on Isolated Boattail Drag of Varying Reynolds Number up to $130 \times 10^6$, NASA TN D-8210, 1976.

16. Reubush, David E.: Effect of Reynolds Number on the Subsonic Boattail Drag of Several Wing-Body Configurations, NASA TN D-8238, 1976.

17. Reubush, David E.: Experimental Investigation to Validate Use of Cryogenic Temperatures to Achieve High Reynolds Numbers in Boattail Pressure Testing, NASA TM X-3396, 1976.

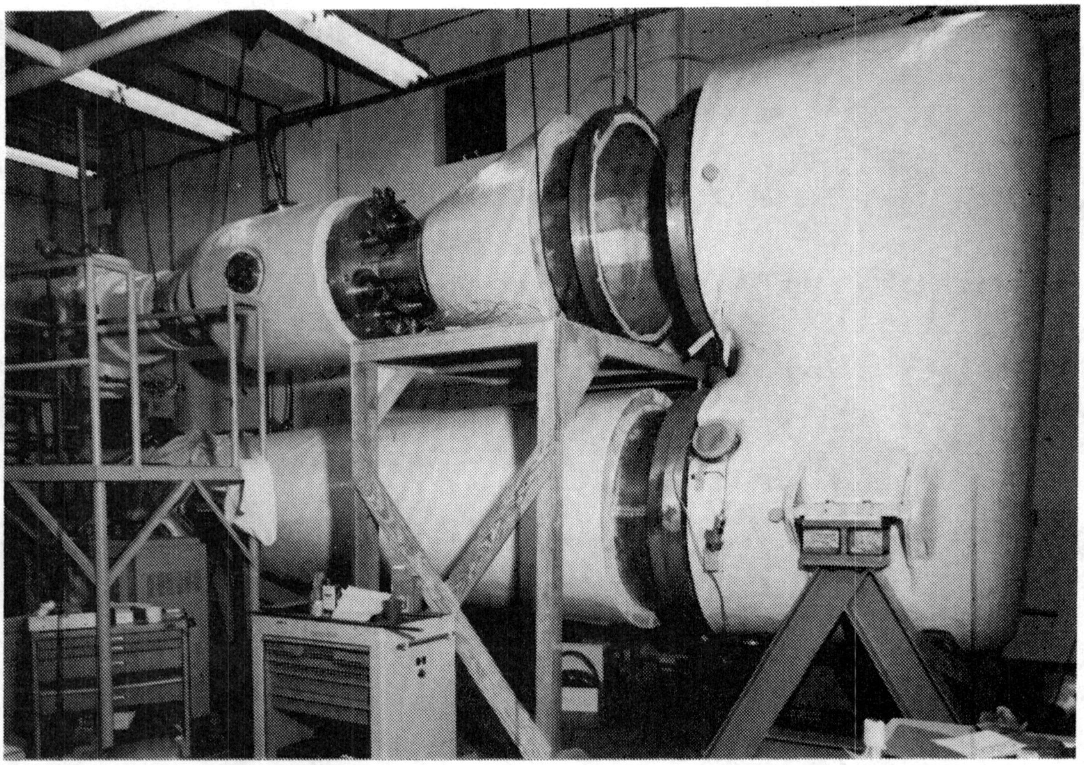


Figure 1.- Installation of pilot tunnel.

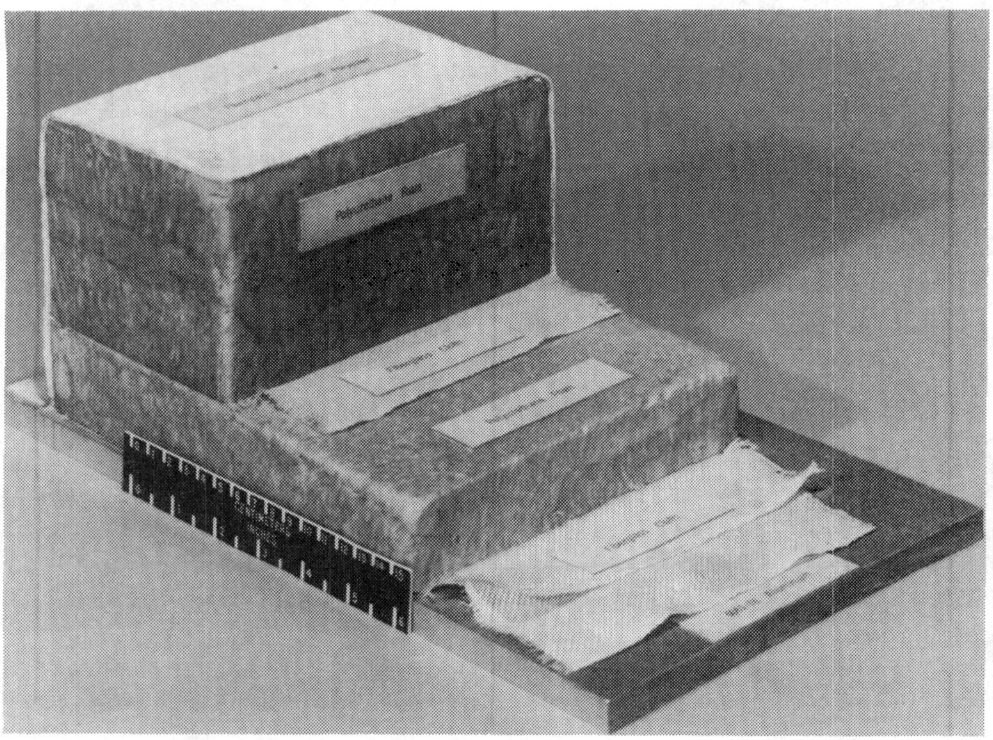


Figure 2.- Original thermal insulation.

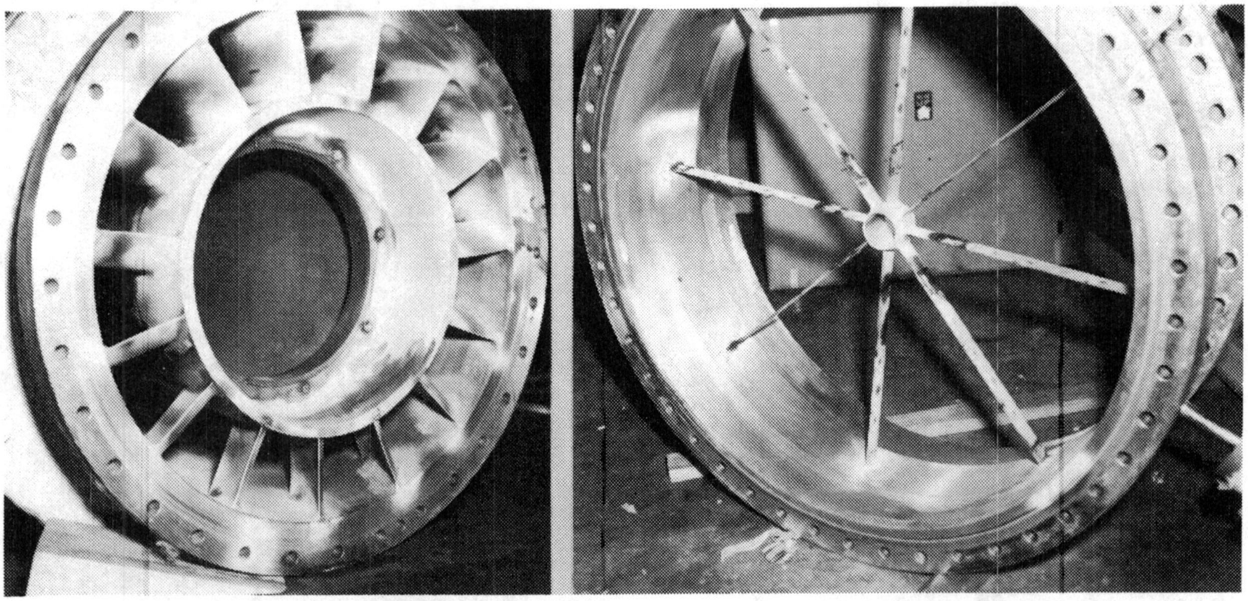


Figure 3.- Internal structural damage.

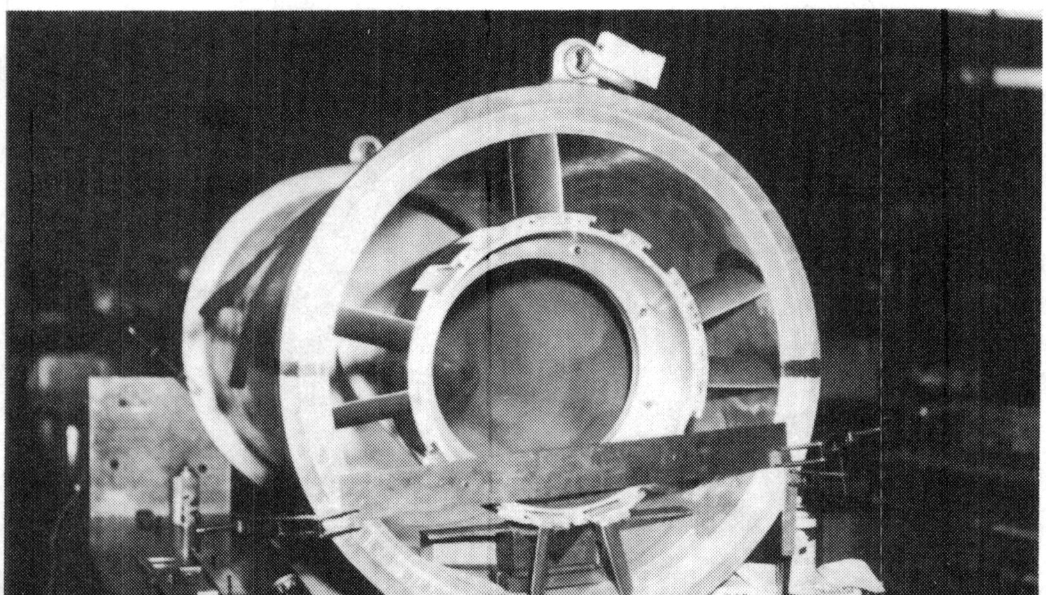


Figure 4.- Internal structural modification of nacelle section.

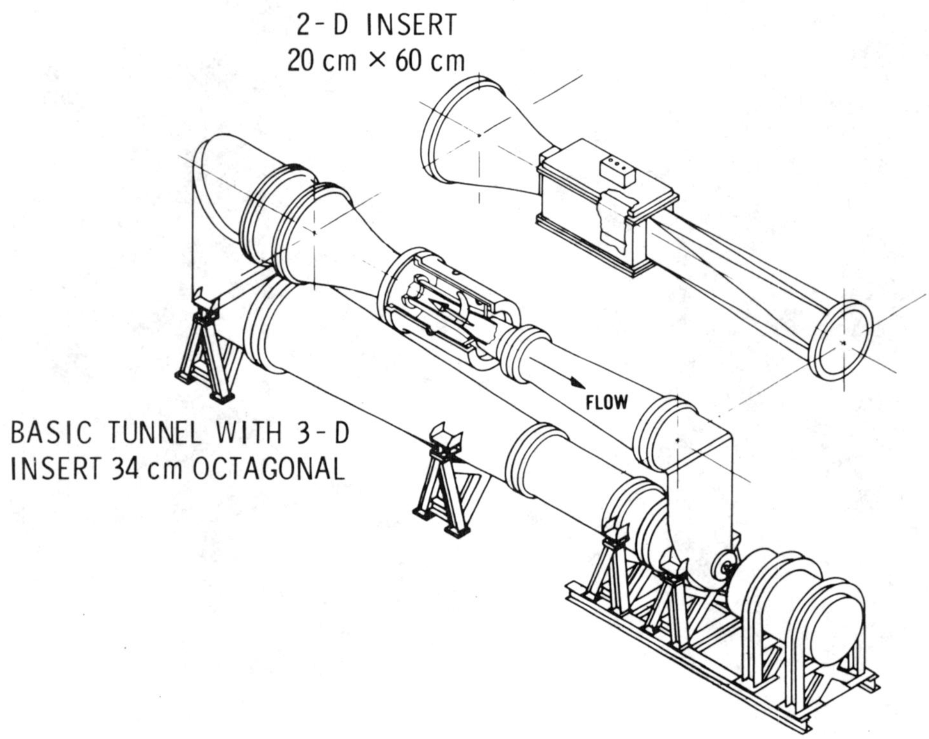



Figure 5.- Interchangeable test section feature. Three-dimensional and two-dimensional, test section inserts.

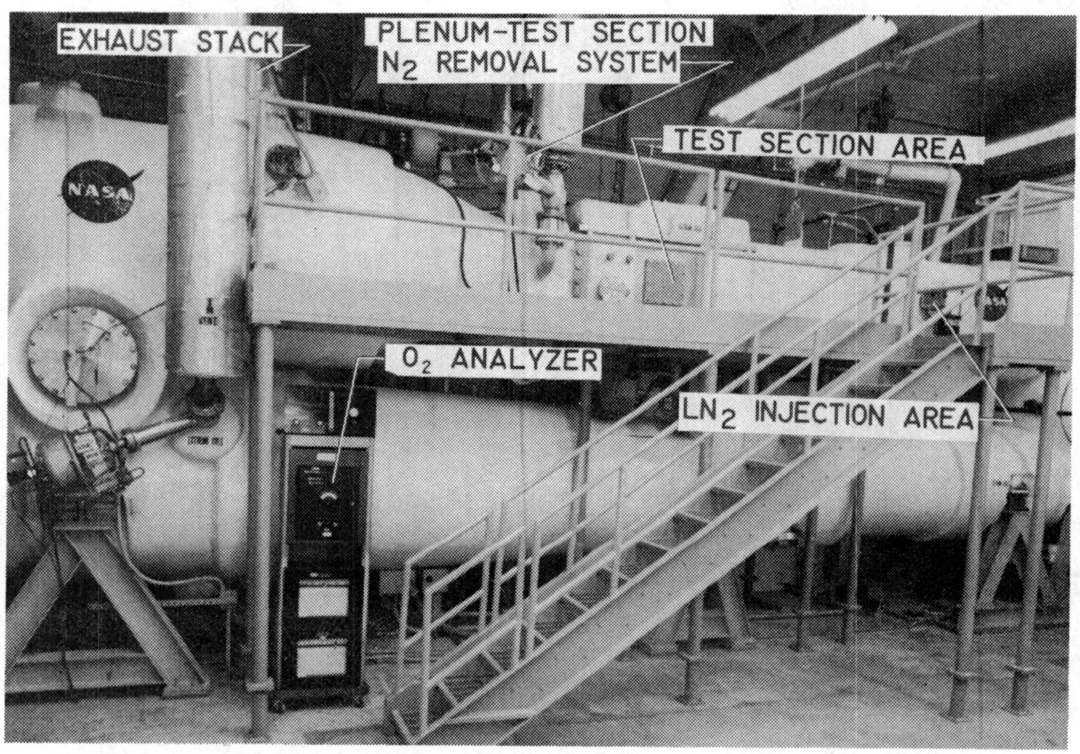



Figure 6.- Photograph of 0.3-m TCT with two-dimensional test section installed.

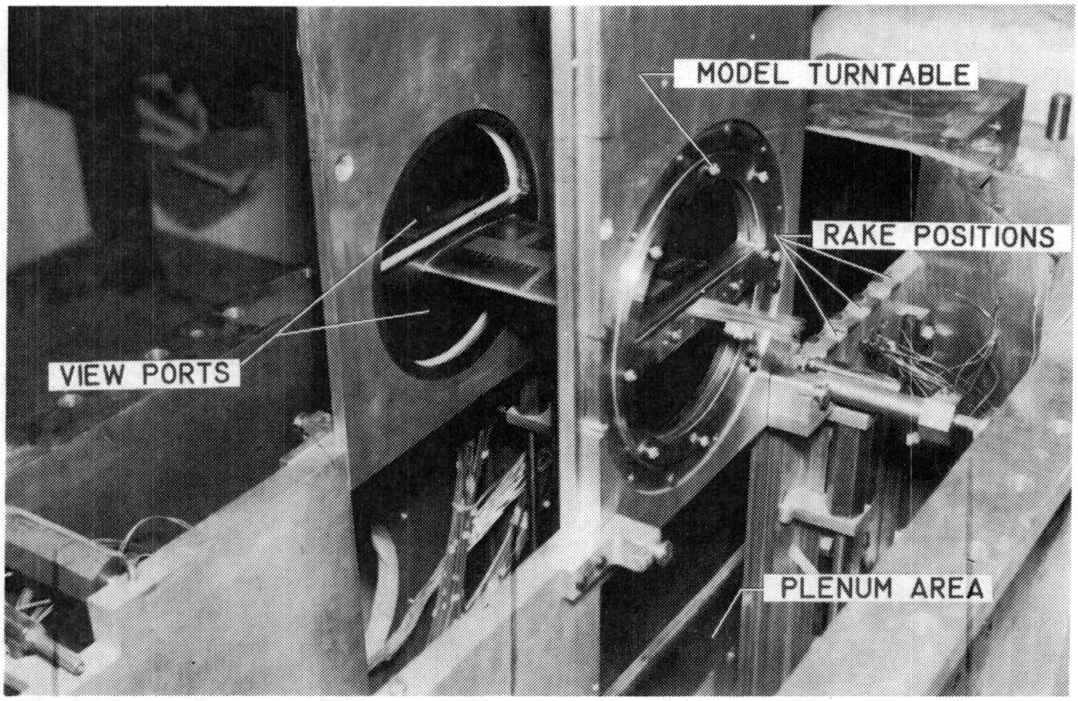



Figure 7.- Removable model module feature of two-dimensional test section.

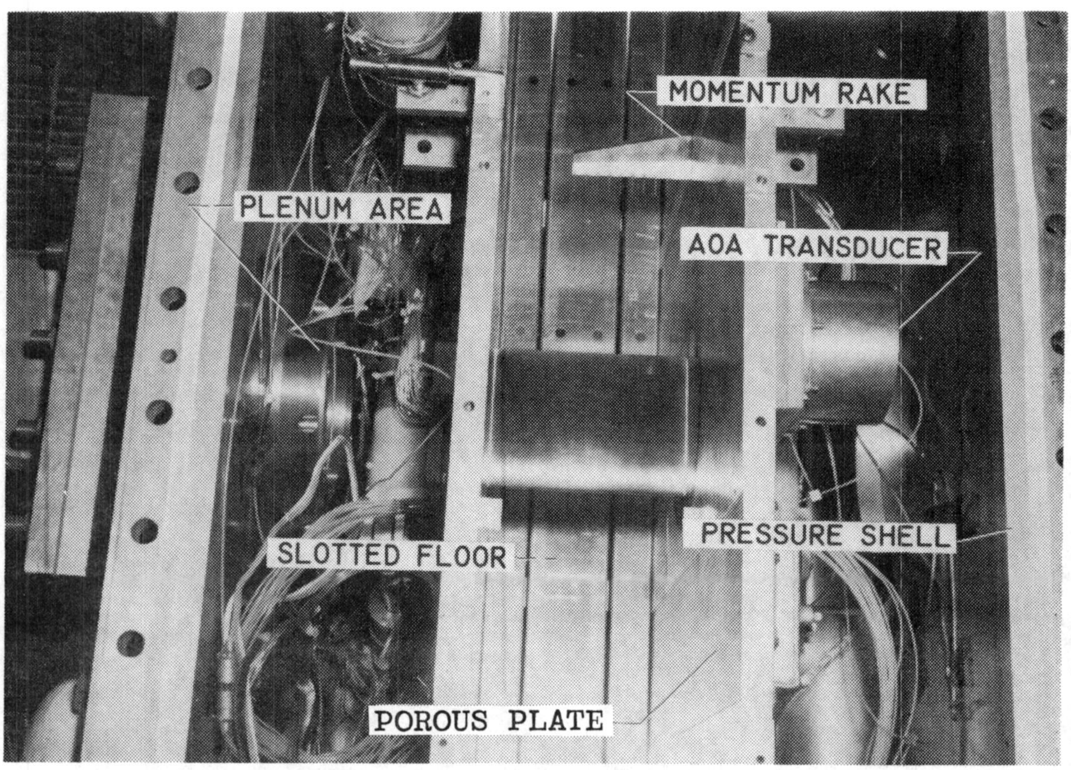



Figure 8.- Top view of two-dimensional test section.

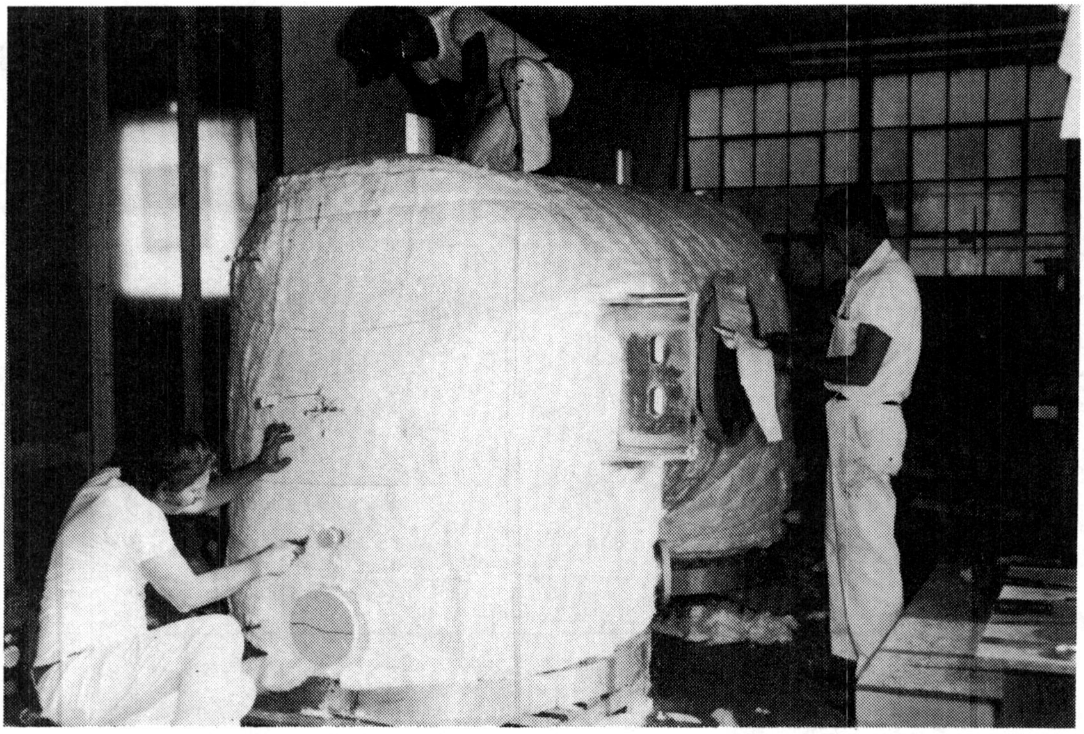


Figure 9.- Current insulation technique.

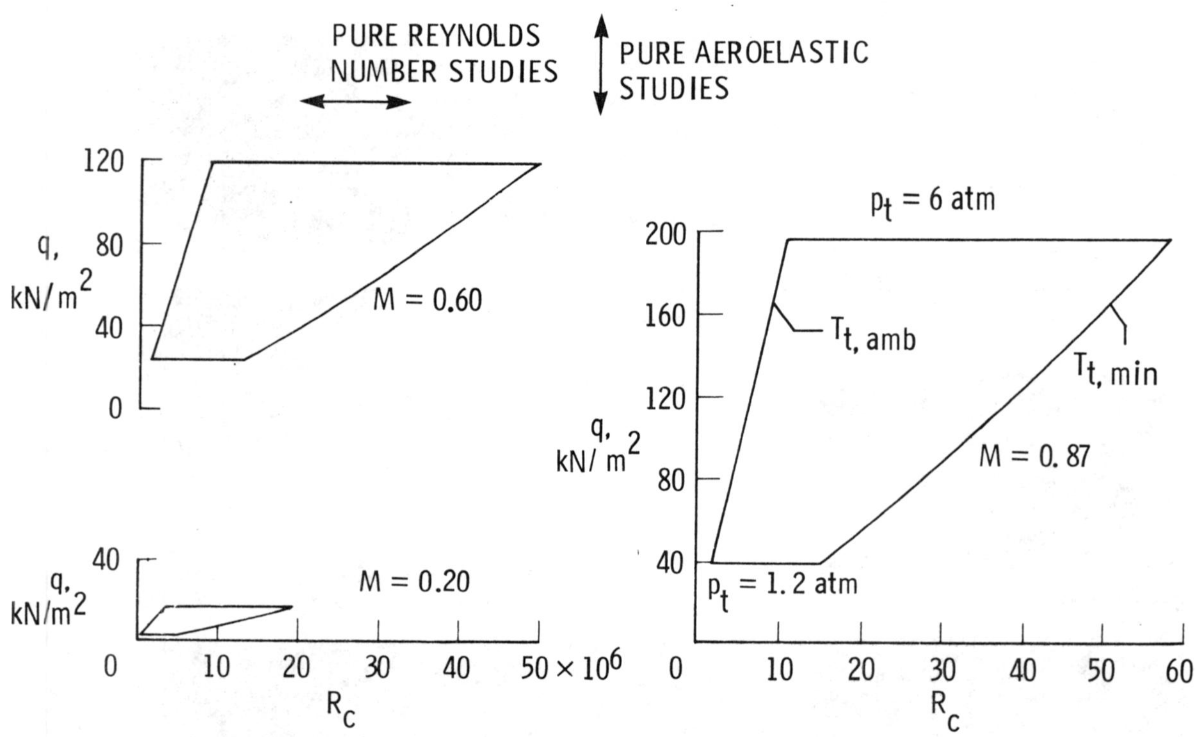



Figure 10.- Reynolds number-dynamic pressure envelopes for two-dimensional test section of 0.3-m TCT.

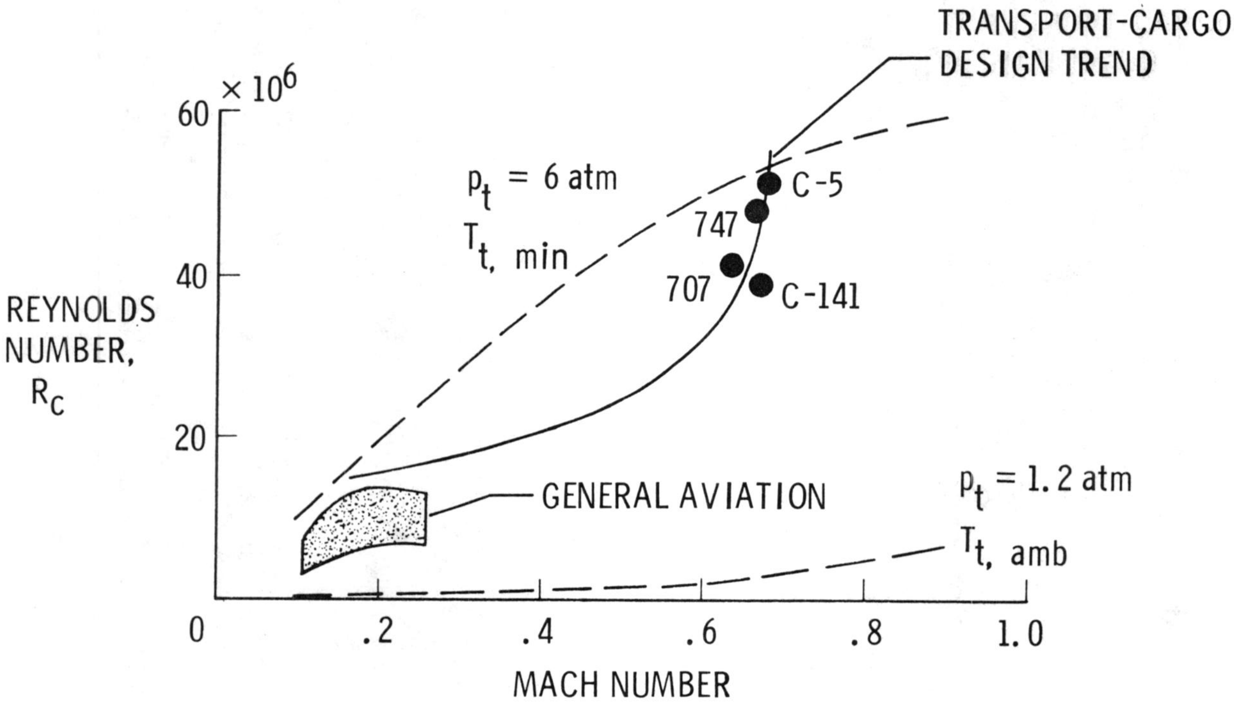



Figure 11.- Reynolds number capability of two-dimensional test section of 0.3-m TCT.

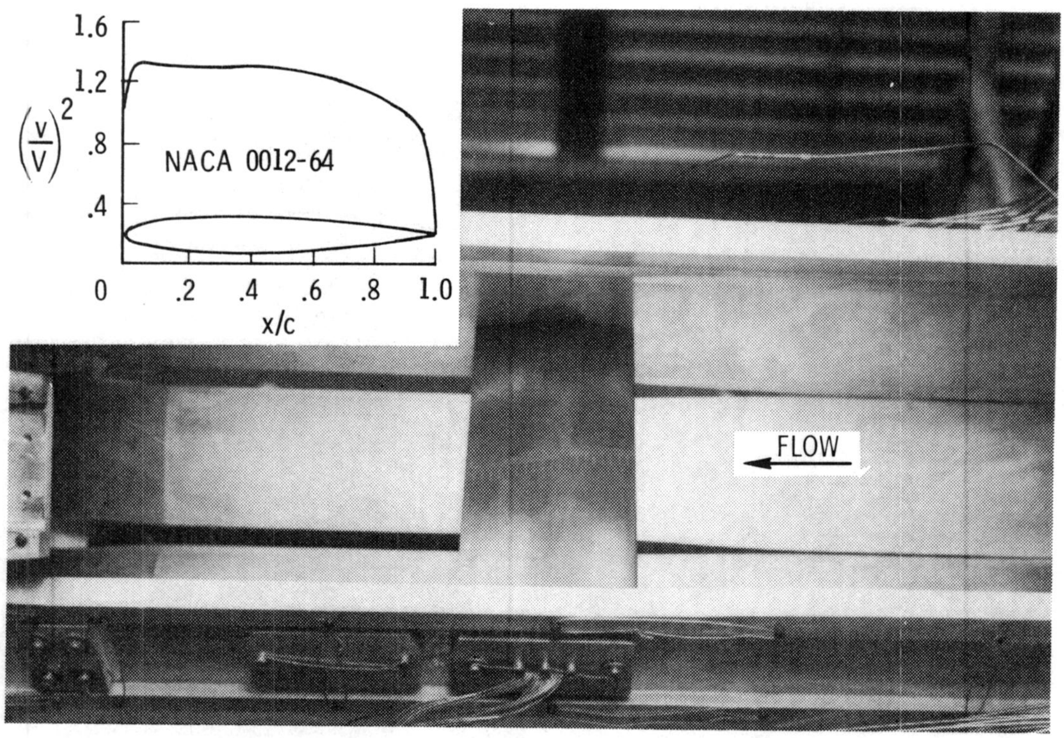



Figure 12.- Photograph of the proof-of-concept model installed in three-dimensional test section.

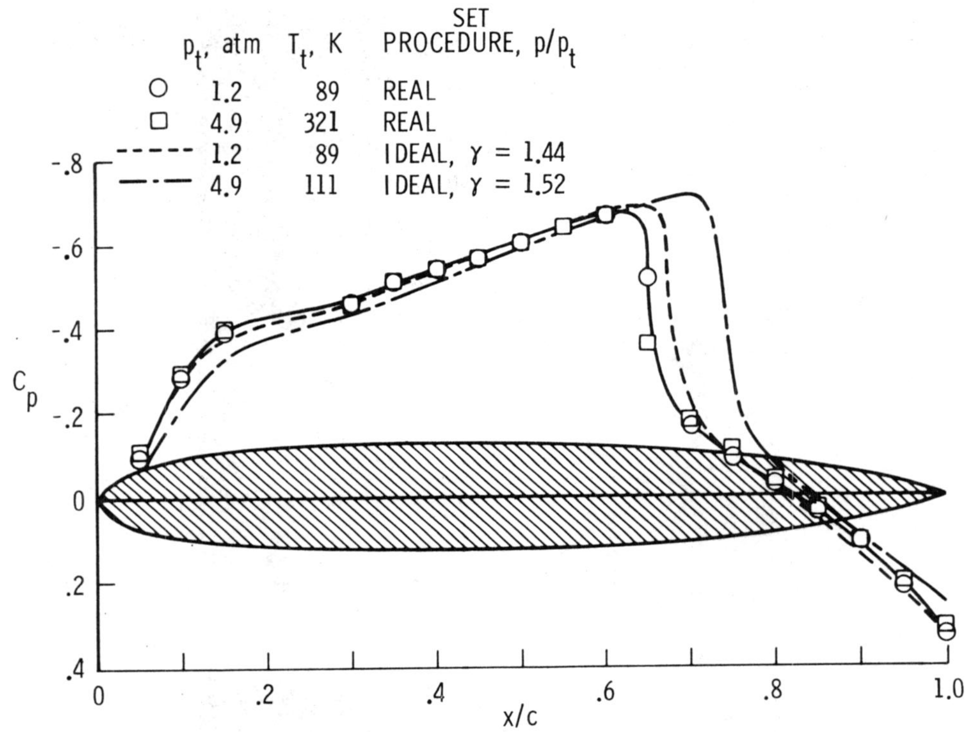



Figure 13.- Typical results obtained during proof-of-concept study. M = 0.85.

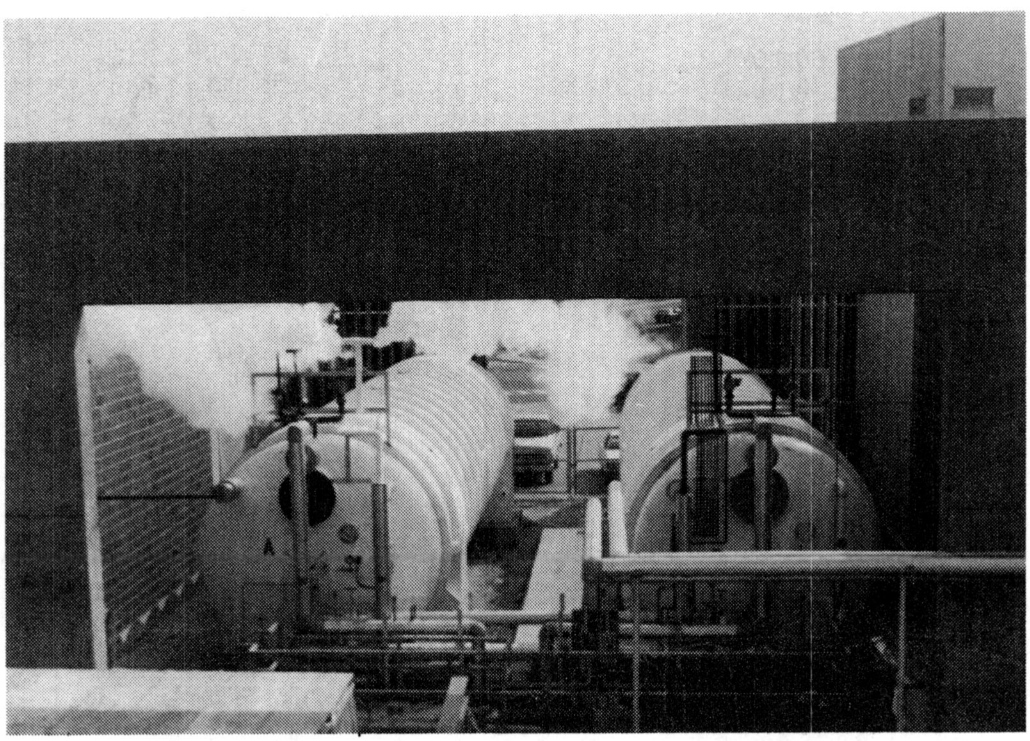


Figure 14.- Current liquid nitrogen storage arrangement for 0.3-m TCT.

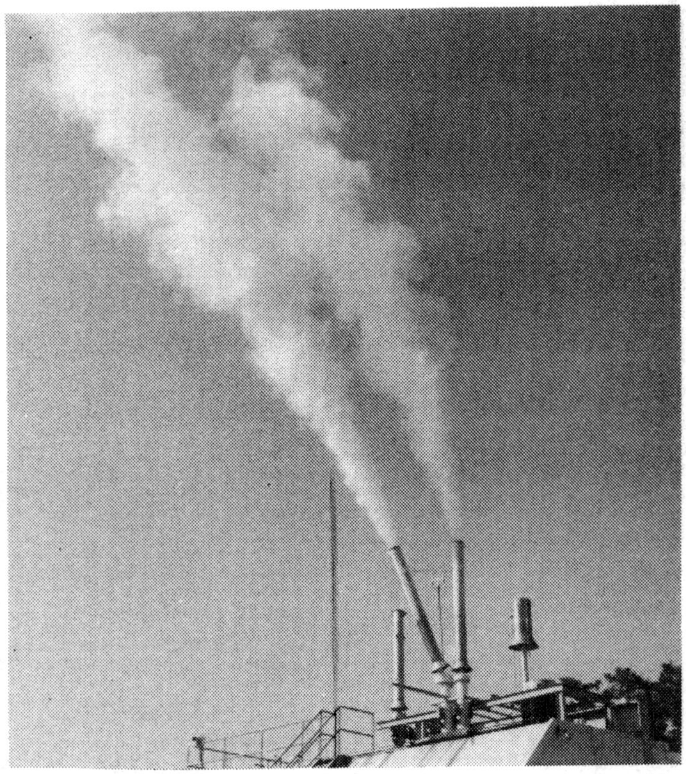


Figure 15.- Nitrogen gas exhaust phase with ejector stacks.

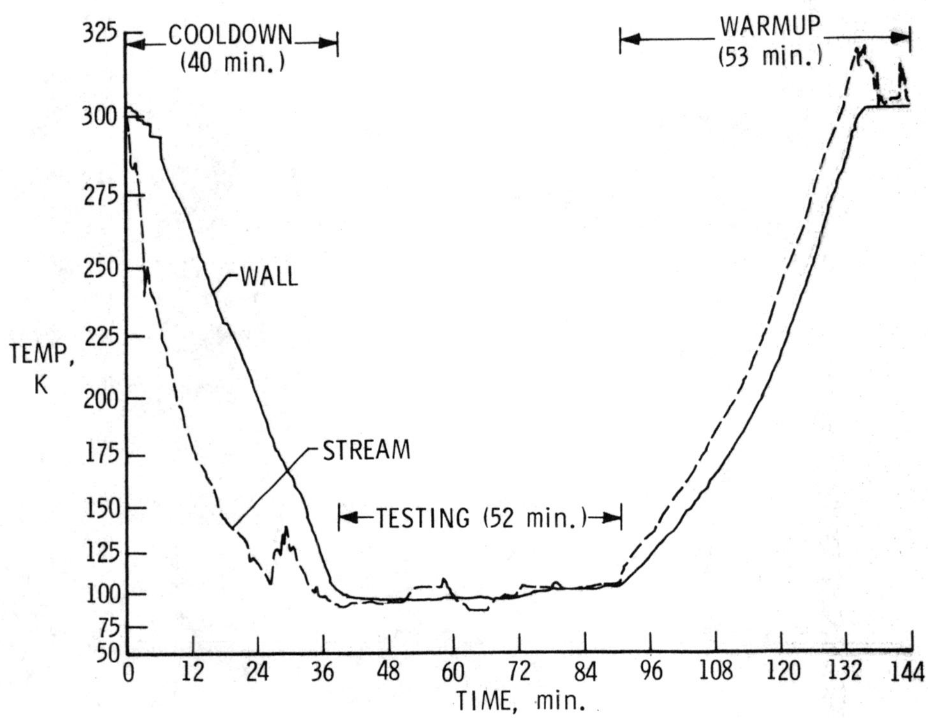



Figure 16.- Wall-stream temperature variation during a typical run.

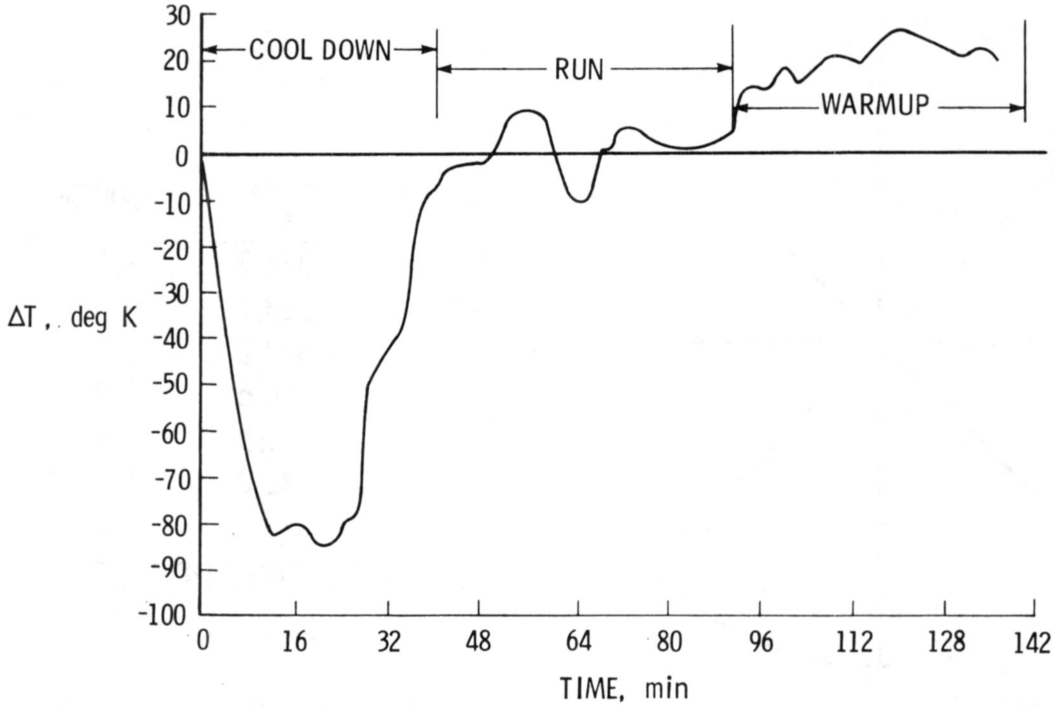



Figure 17.- Temperature difference between wall and stream.

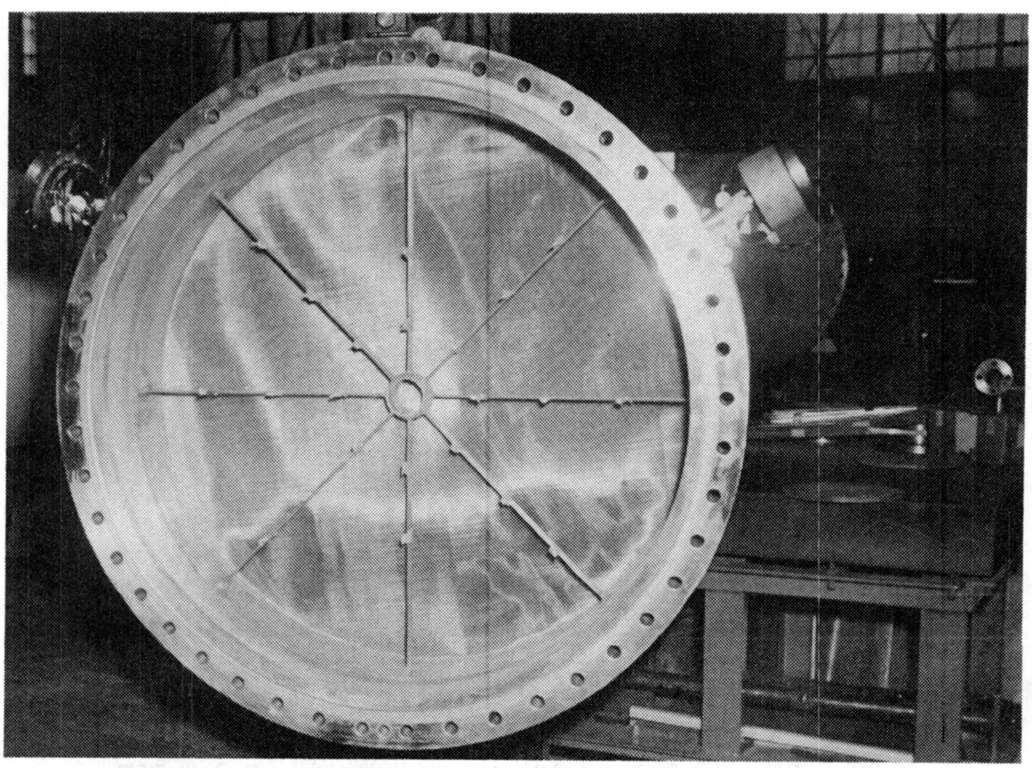
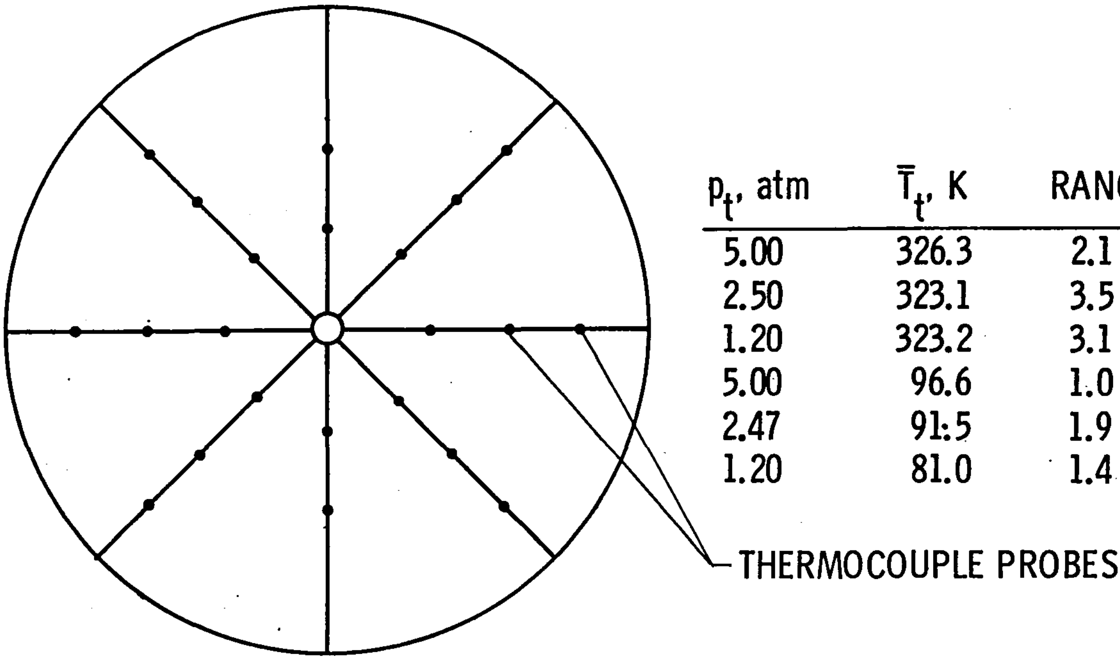


Figure 18.- Photograph of temperature surveying installed in screen section of tunnel.

M = 0.85




| $p_t$, atm | $\bar{T}_t$, K | RANGE | σ |
|---|---|---|---|
| 5.00 | 326.3 | 2.1 | 0.6 |
| 2.50 | 323.1 | 3.5 | 1.0 |
| 1.20 | 323.2 | 3.1 | 0.9 |
| 5.00 | 96.6 | 1.0 | 0.3 |
| 2.47 | 91.5 | 1.9 | 0.4 |
| 1.20 | 81.0 | 1.4 | 0.3 |

Figure 19.- Typical temperature results obtained from temperature survey rig.

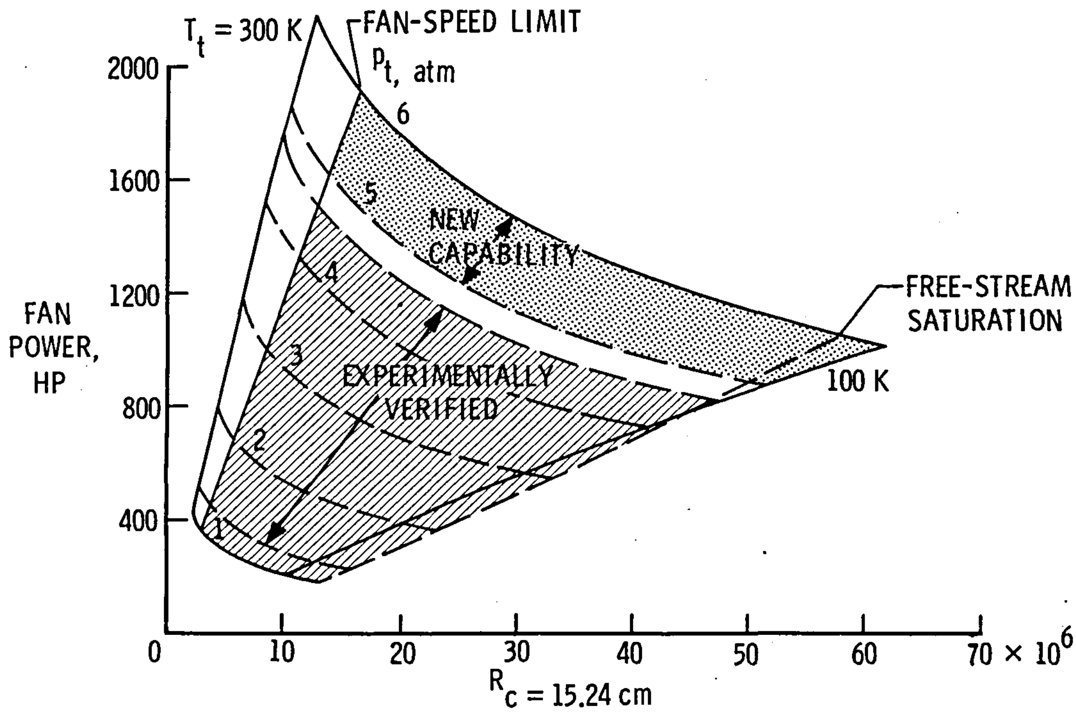



Figure 20.- Fan power-Reynolds number map for 0.3-m TCT for M = 0.85.

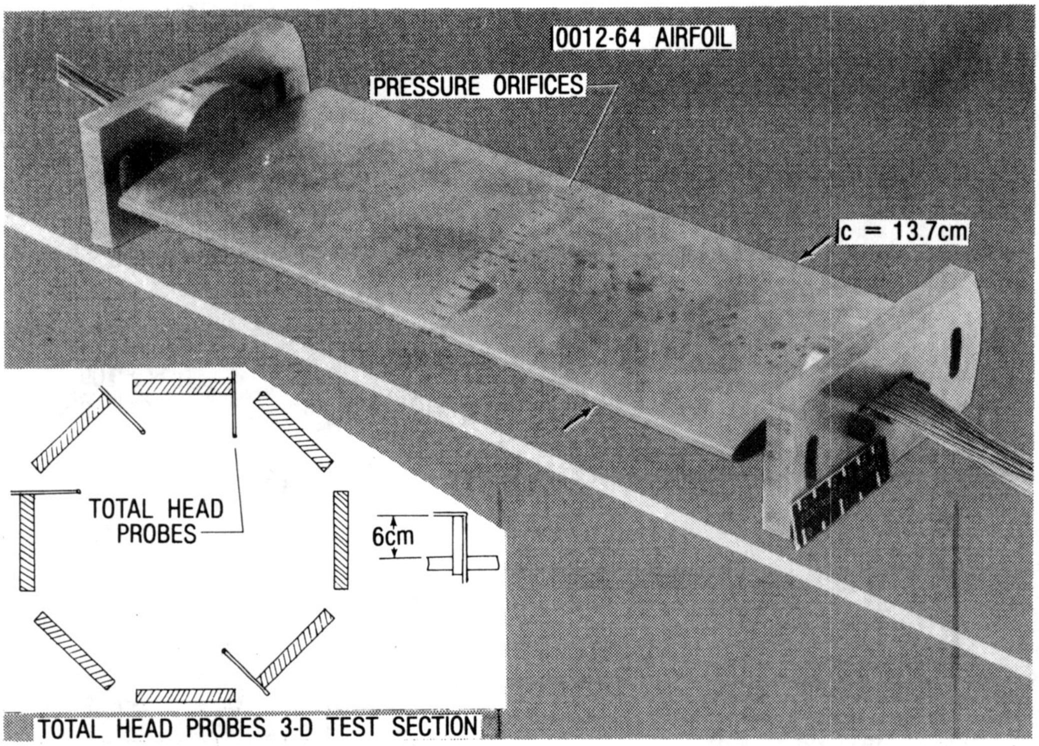



Figure 21.- Experimental devices utilized in initial condensation studies.

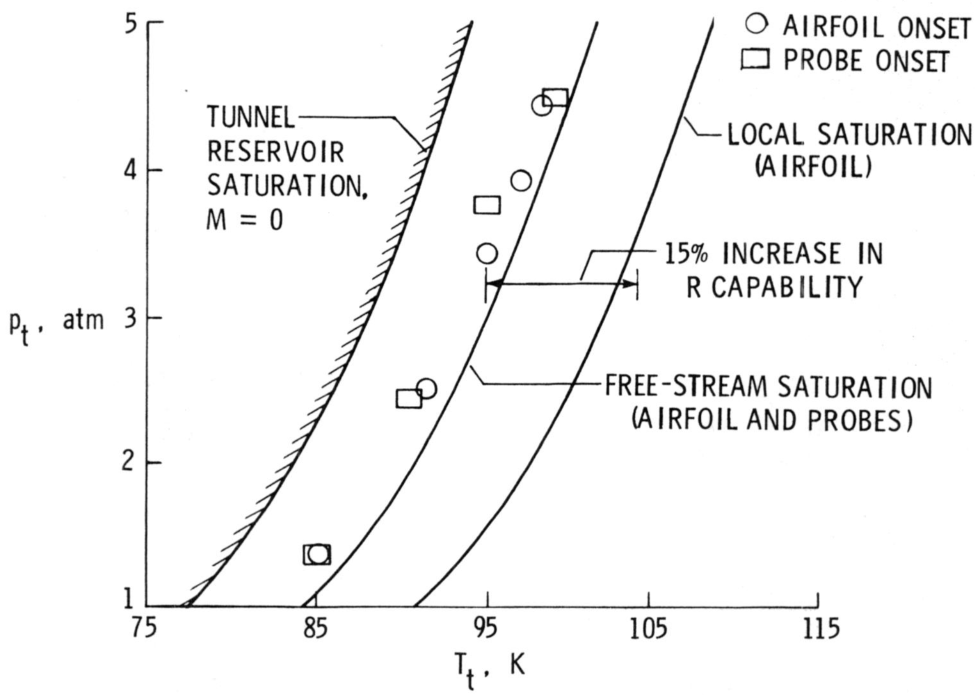



Figure 22.- Typical Reynolds number increase due to operating below local saturation temperature. M = 0.85.

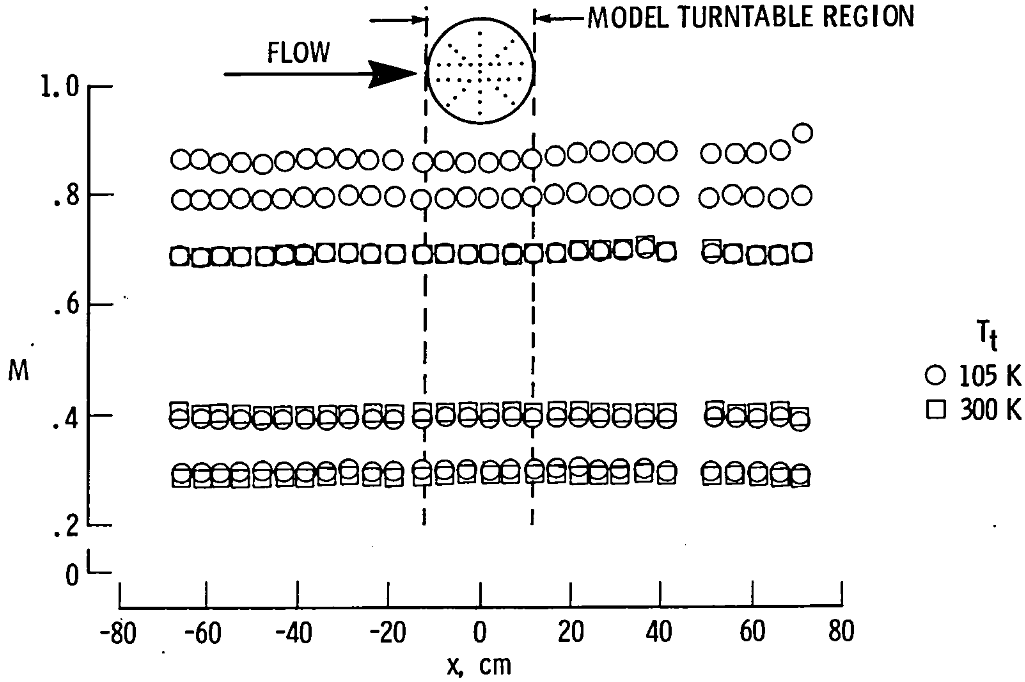
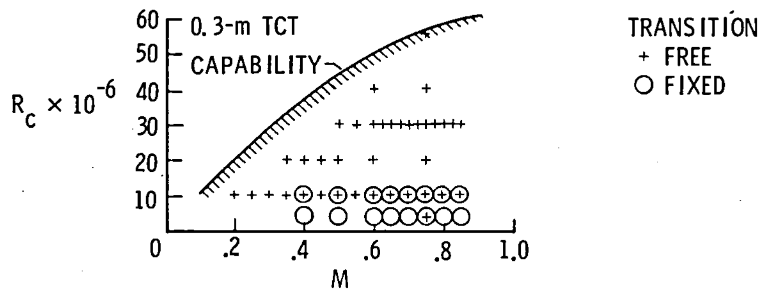
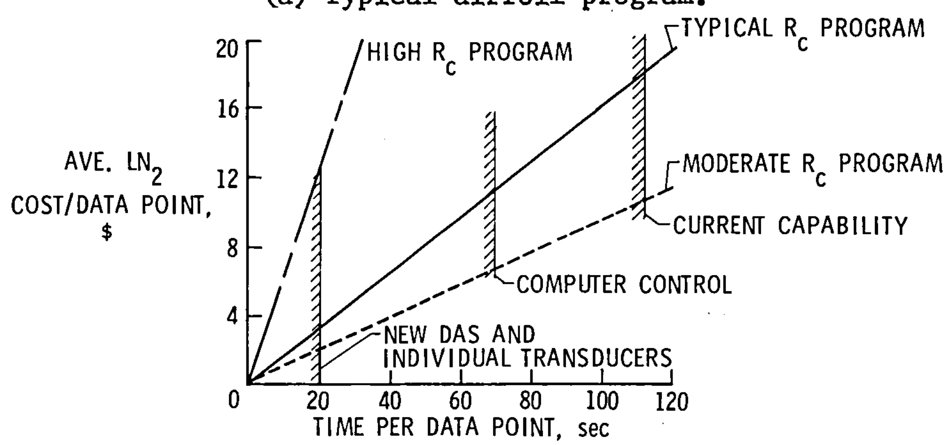



Figure 23.- Typical calibration results obtained in two-dimensional test section of 0.3-m TCT. $p_t \approx 4.7$ atm.




(a) Typical airfoil program.




(b) Nitrogen cost (does not include cool-down).

Figure 24.- Typical airfoil test program and liquid nitrogen cost trends.

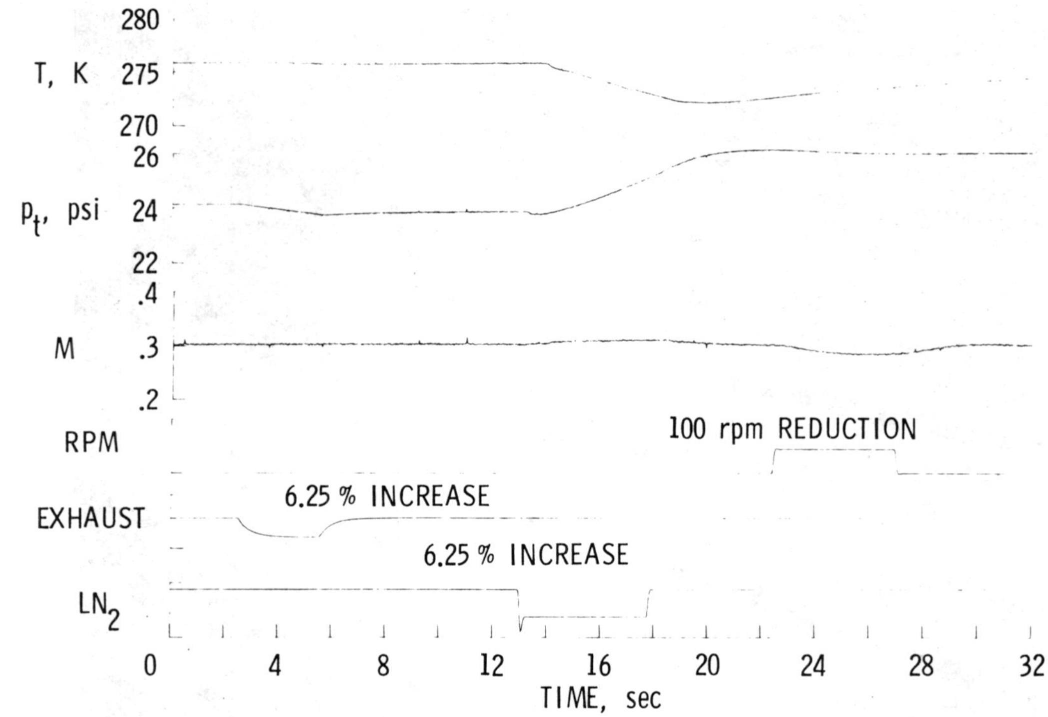



Figure 25.- Results obtained during initial dynamic response study.

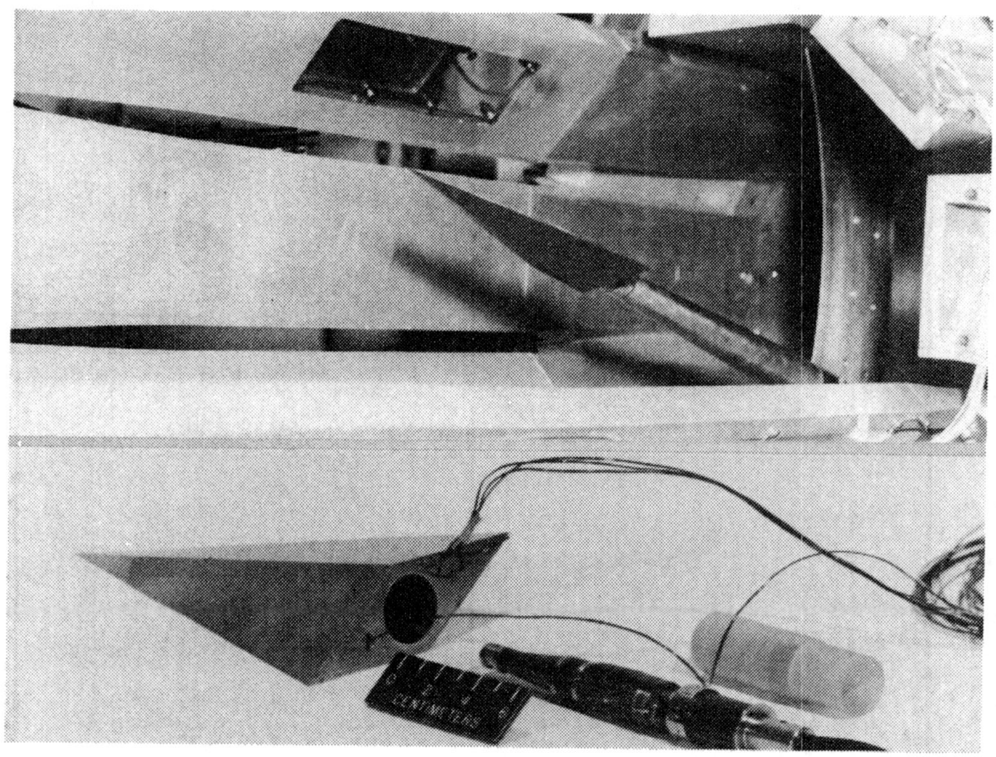


Figure 26.- Photographs of balance model installed in three-dimensional test section and model-balance-insulation shield configuration.

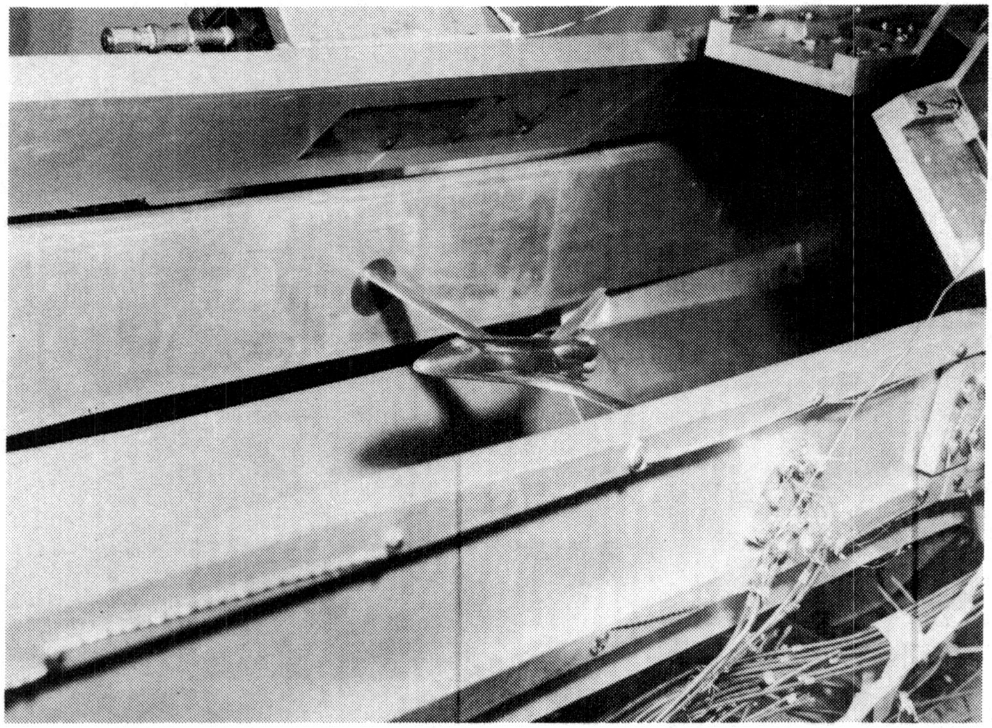


Figure 27.- Photograph of space shuttle model installed in three-dimensional test section.

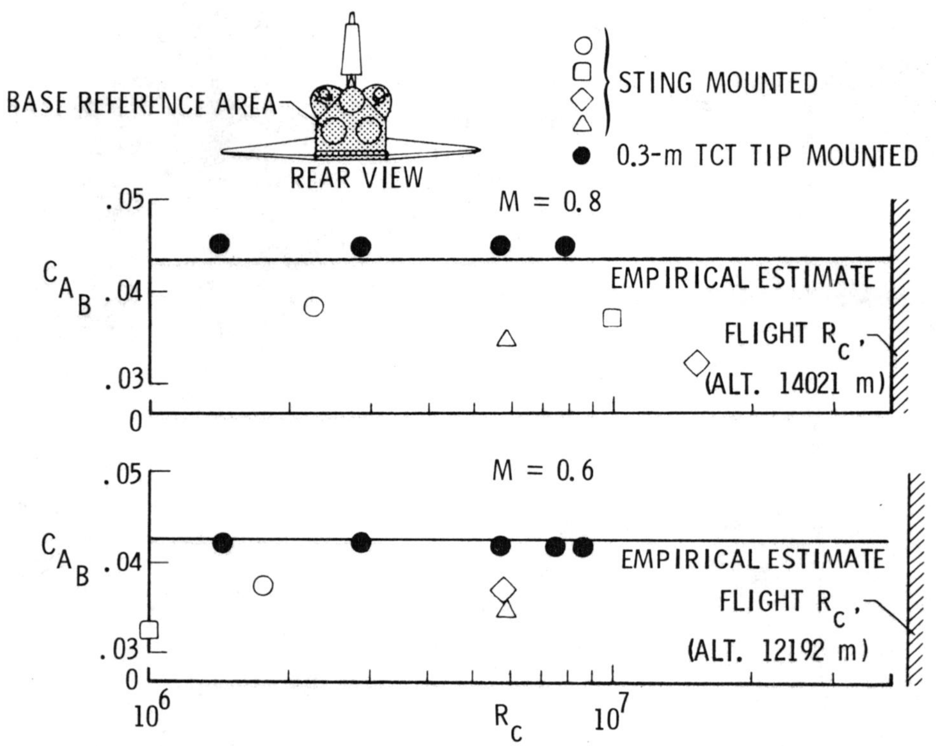



Figure 28.- Typical axial force results obtained during space shuttle studies. $\alpha = 0^o$.

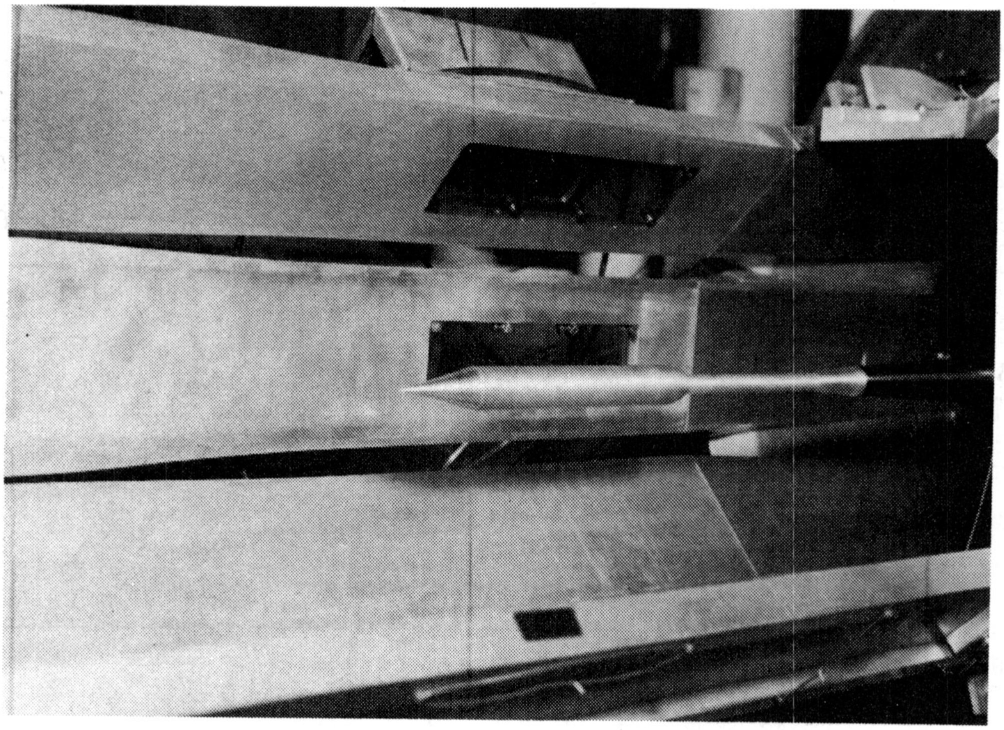


Figure 29.- Photograph of boattail model installed in three-dimensional test section.

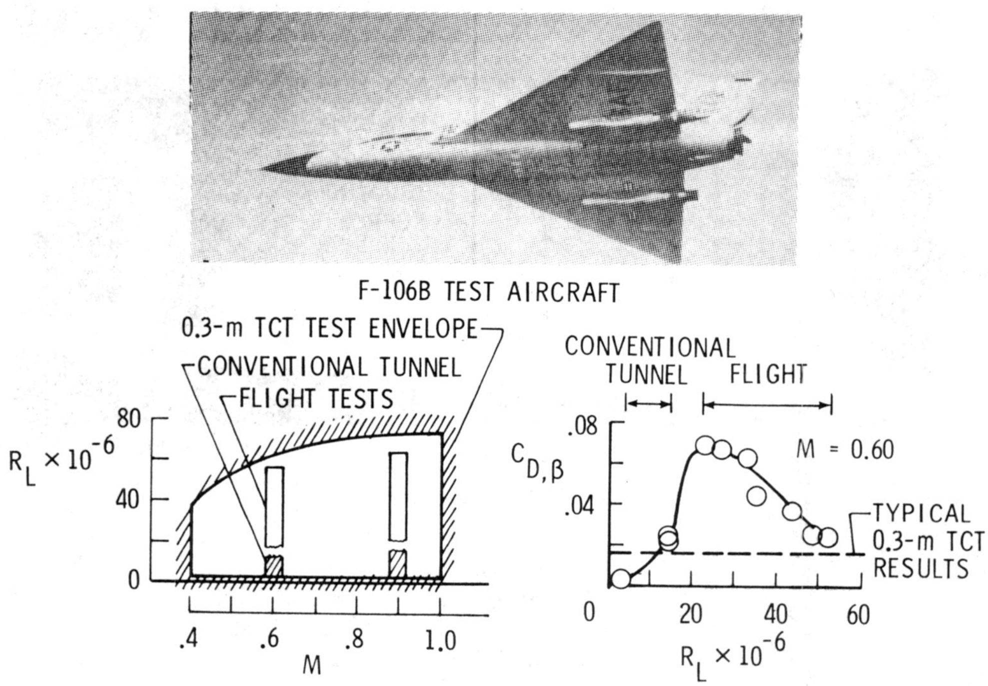



Figure 30.- Comparison of wind tunnel and flight boattail drag results.

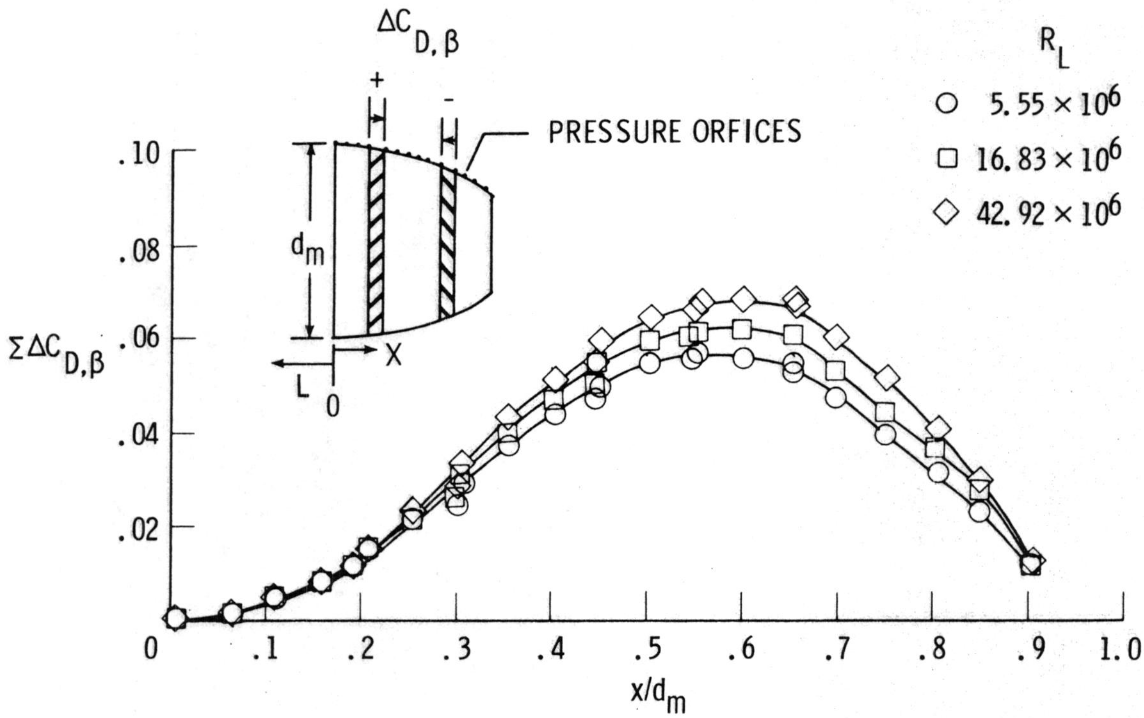



Figure 31.- Typical effects of Reynolds number on boattail drag, M = 0.60.

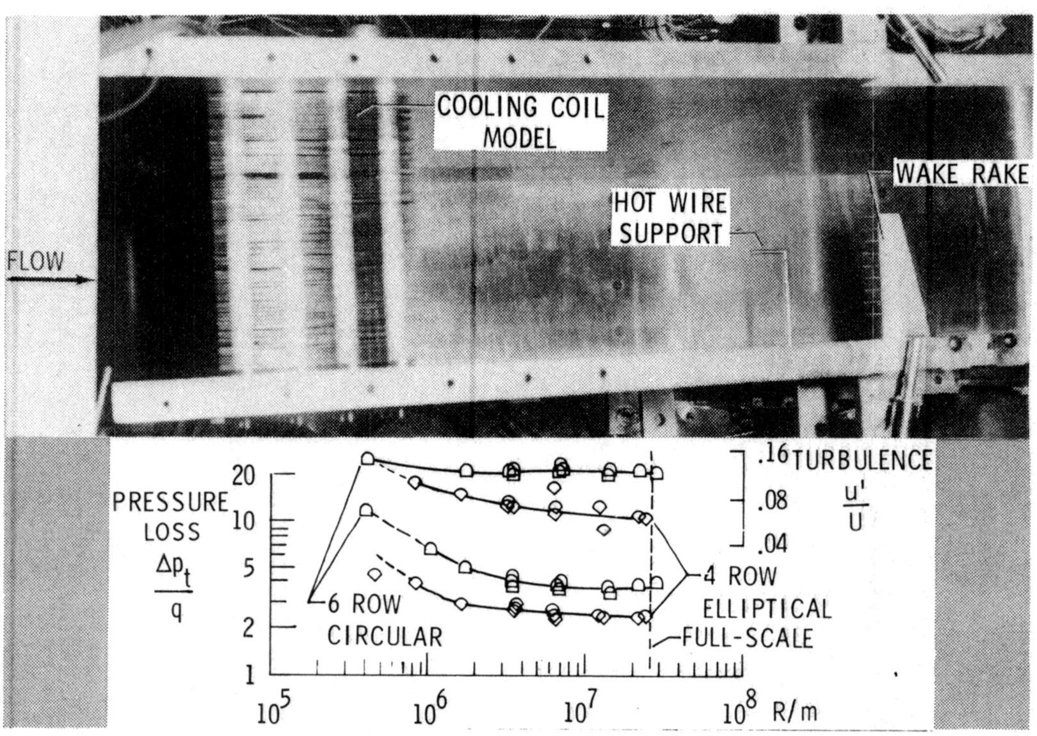



Figure 32.- Results obtained in full-scale cooling coil study.

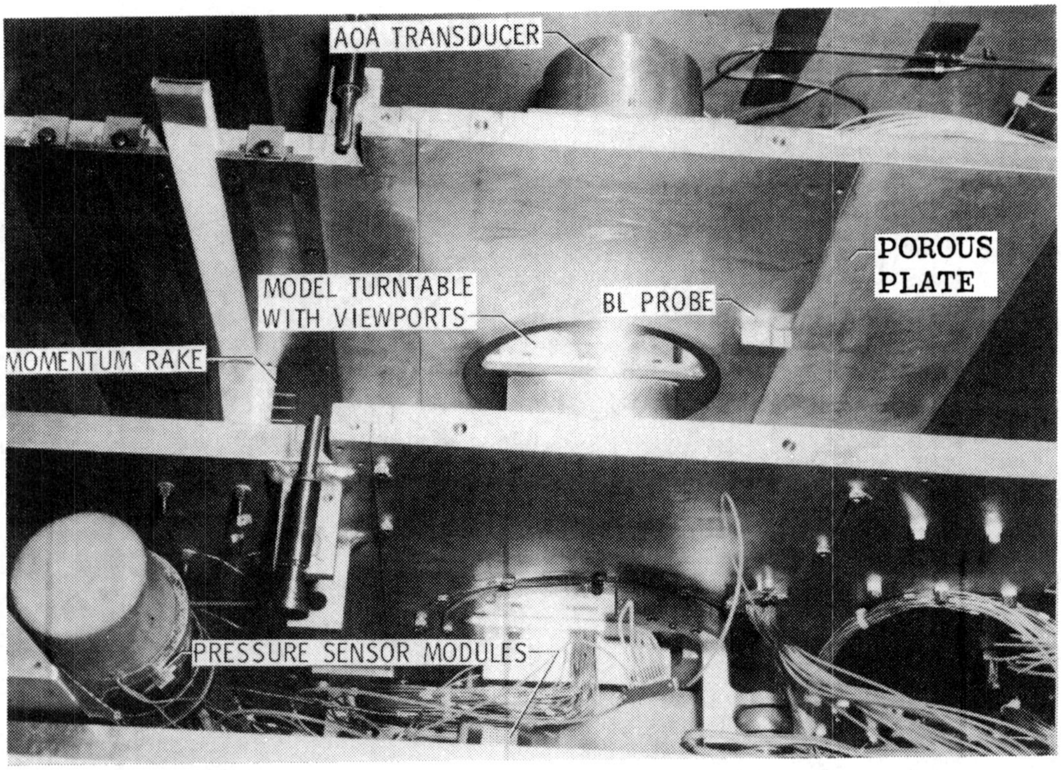



Figure 33.- Photograph of 0012 model installed in two-dimensional test section.

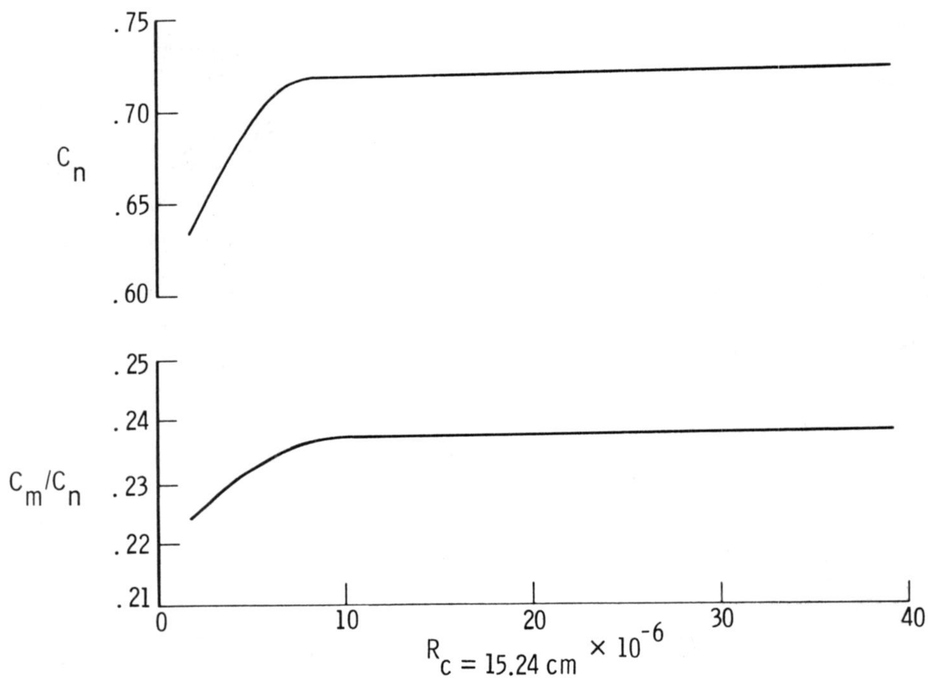



Figure 34.- Results obtained during a study of 0012 airfoil. $M = 0.60$, $\alpha \approx 6^{o}$.

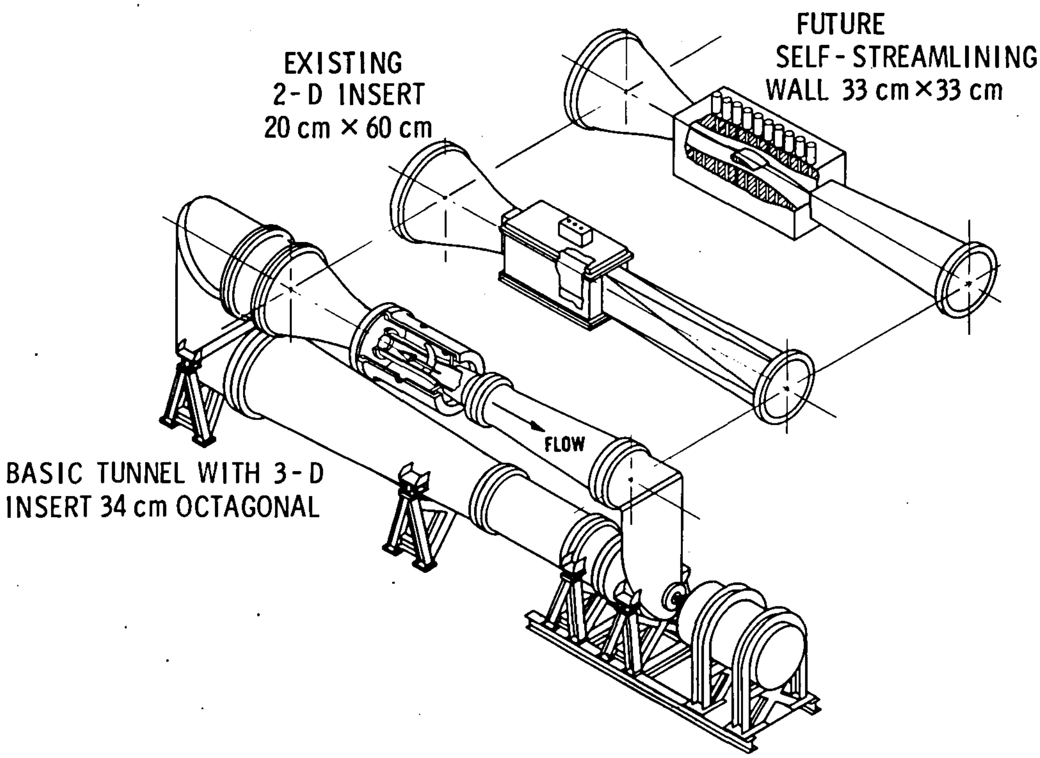



Figure 35.- Interchangeable test section feature. Three-dimensional, two-dimensional, and flexible wall inserts.

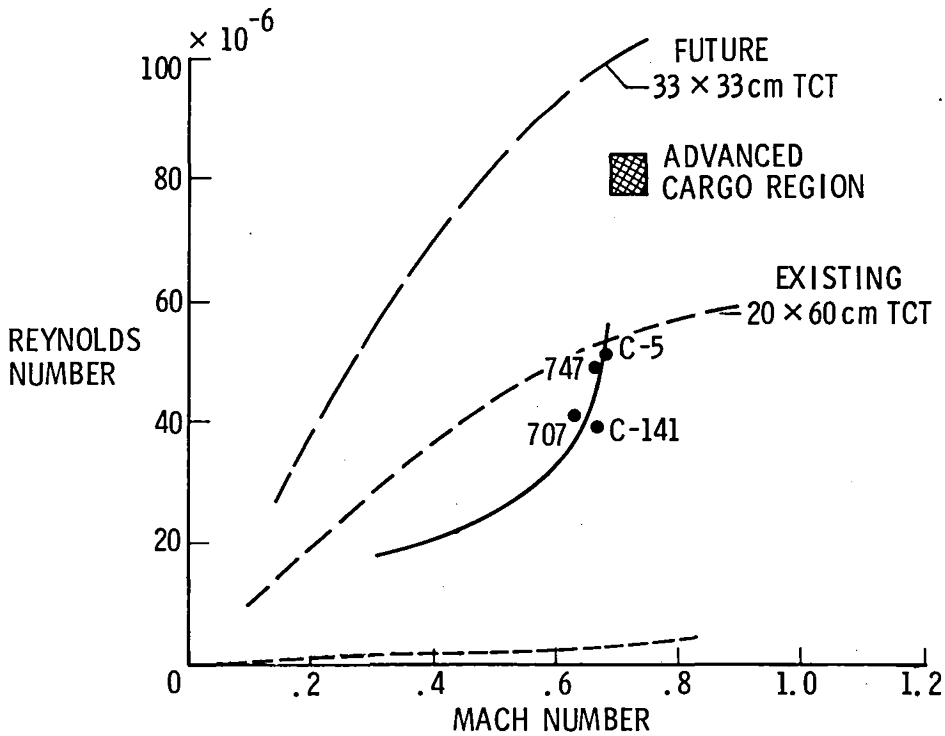



Figure 36.- Airfoil capabilities of 0.3-m TCT.

1. Report No.
NASA TM-80123

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
REVIEW OF DESIGN AND OPERATIONAL CHARACTERISTICS OF THE 0.3-METER TRANSONIC CRYOGENIC TUNNEL

5. Report Date
September 1979

6. Performing Organization Code

7. Author(s) Edward J. Ray, Charles L. Ladson, Jerry B. Adcock, Pierce L. Lawing, and Robert M. Hall

8. Performing Organization Report No.

10. Work Unit No.
505-06-43-08

9. Performing Organization Name and Address
NASA Langley Research Center
Hampton, Virginia 23665

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Memorandum

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546

14. Sponsoring Agency Code

15. Supplementary Notes
This paper was presented at the First International Symposium on Cryogenic Wind Tunnels, The University, Southampton, England, April 3-5, 1979.

16. Abstract

The past 6 years of operation with the NASA Langley 0.3-m Transonic Cryogenic Tunnel (TCT) have shown that there are no insurmountable problems associated with cryogenic testing with gaseous nitrogen at transonic Mach numbers. The fundamentals of the concept have been validated both analytically and experimentally and the 0.3-m TCT, with its unique Reynolds number capability, has been used for a wide variety of aerodynamic tests. Techniques regarding real-gas effects have been developed and cryogenic tunnel conditions can be set and maintained accurately. It has been shown that cryogenic cooling by injecting liquid nitrogen directly into the tunnel circuit imposes no problems with temperature distribution or dynamic response characteristics. Experience with the 0.3-m TCT has, however, indicated that there is a significant learning process associated with cryogenic, high Reynolds number testing. Many of the questions have already been answered; however, factors such as tunnel control, run logic, economics, instrumentation, and model technology present many new and challenging problems.

17. Key Words (Suggested by Author(s))
Cryogenic tunnel
Design characteristics
Operating experience
Operating envelopes

18. Distribution Statement
Unclassified - Unlimited
Subject Category - 02

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price* |
|---|---|---|---|
| Unclassified | Unclassified | 55 | $5.25 |

* For sale by the National Technical Information Service, Springfield, Virginia 22161